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FREIGHT TRAIN RESISTANCE

ITS RELATION TO AVERAGE CAR WEIGHT

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FREIGHT TRAIN RESISTANCE:

ITS RELATION TO AVERAGE CAR WEIGHT

PART I

I. INTRODUCTION

1. *Preliminary.*—Train resistance varies not only with the train speed, but also with the average weight of the cars of which the train is composed. At a given speed the tractive effort required for each ton of weight of the train will be greater, for example, for the train which is composed of cars of 20 tons average gross weight, than for the train composed of cars which weigh, on the average, 50 tons each.

While this fact has been known for some years, it has found inadequate expression and but little application. In the establishment of their tonnage ratings, many railroads have altogether ignored it. In the tonnage ratings of a few roads, this variation of resistance with car weight is recognized to the extent of allowing a difference in rating between trains composed of loaded cars and those consisting entirely or partially of empty cars. Generally, in such systems, a certain amount is allowed arbitrarily to be added to the weight of empty cars in determining, for the purpose of rating, the weight of the train in which they are found. In such rating no distinction is made between loaded cars of various weights although such weights vary from 25 to 70 tons. A still smaller group of railroads have fully recognized the significance of the facts above stated in establishing their tonnage ratings, which, in such cases, are usually termed "adjusted" or "equated" ratings. Under these adjusted ratings, the actual weight of the train allotted to a particular locomotive varies according to the number of cars in the train. The ratings for the same locomotive, with trains of 40, 60, and 80 cars, for example, will be different in each of the three cases. This is, in effect, a variation of the rating with respect to the average car weights. Most of these adjusted ratings have been empirically determined. In the few cases where they rest upon experiments made to determine the variations in train resistance with respect to car weight, the data and results of such experiments have not been fully published.

Existing train resistance formulas likewise fail in most cases to take into account these variations of resistance with car weight, and probably much of the divergence among them is properly to be ascribed to this fact.

2. *Purpose of the Tests.*—In view of the facts just stated, it has seemed desirable to make the tests whose results are here recorded. They were planned to determine the resistance of freight trains under the usual conditions of operation; and they were designed to disclose at the same time, if possible, the relation existing, at any given speed, between train resistance and average car weight. Since the chief use of such information is in the production of locomotive ratings, the conditions of the tests have been made like those which prevail in normal freight train operation. The speed range, for example, is from 5 to 35 miles per hour; and the trains experimented upon were trains in regular service, and usual in their make-up. The track upon which the tests were made is believed to be representative of good main-line construction.

The tests have been conducted by the Railway Engineering Department of the University of Illinois as part of the research work of the Engineering Experiment Station. They were begun in April, 1908, and were completed in May, 1909. All tests were made by means of Test Car No. 17, a dynamometer car, owned jointly by the University of Illinois and the Illinois Central Railroad, and were carried out on the Chicago division of this road.

In Part I of this report, the aim has been to present as brief a statement of the results and conditions as is compatible with a clear understanding of the tests. It consists, accordingly, of a discussion of the results of the experiments, prefaced by a general statement of conditions and methods. The final results are exhibited in Fig. 11, in Table 3, and in equations 1 to 13, on pages 33, 34, and 35. A summary of the test conditions and the conclusions is inserted on pages 5 to 7. Part II of the report has been added in order to complete the record so that those interested in the details may verify or modify the results and conclusions presented in Part I. It consists of appendixes in which the aim has been to state fully all the conditions of track, weather, and train make-up, as well as to present the test data, the methods of calculation, and the results.

Throughout the report, the terms "resistance" and "train resistance" mean the number of pounds of tractive effort required for each ton of the train in order to keep it in motion on straight and level track, at uniform speed, and in still air. The report deals exclusively with the resistance of the train behind the locomotive tender. Locomotive and tender resistance are not discussed.

3. *Acknowledgments.*—The tests have been made possible through the interest and cooperation of Mr. William Renshaw, Mr. J. G. Neuffer, and Mr. R. W. Bell, who were successively superintendents of machinery of the Illinois Central Railroad, during the period of planning and conducting the work. Many other officials of the Chicago division of the road have rendered generous assistance in the investigation, which has entailed for them not a little inconvenience and labor. Such interest and assistance are thoroughly appreciated by those of the University staff who have been concerned with the work.

Throughout the tests, the operation of the dynamometer car and the making of the calculations have been under the direct supervison of F. W. Marquis, Associate in the Railway Engineering Department, Engineering Experiment Station. Much of whatever accuracy and reliability have been attained in the investigation is due to his intelligent and painstaking care in making the tests and in systematizing the work of calculation. He has also rendered great assistance in supervising the preparation of the tables and illustrations, and in the final checking of the manuscript.

II. SUMMARY AND CONCLUSIONS

4. *Summary.*—The report deals with the results obtained from tests of 32 ordinary freight trains, whose chief characteristics were as follows:

	Minimum	Maximum
Total weight, tons	747	2908
Average weight per car, tons	16.12	69.92
Number of cars in the train	26	89

The trains whose average weights were less than 20 tons or more than 60 tons were composed of cars of nearly uniform weight; while those whose average car weights were between 20 and 60 tons were either homogeneous or mixed as regards the weight of the individual cars.

The weather during the tests was generally fair. The minimum air temperature during any test was 34°F. the maximum 82°F. The approximate average wind velocity prevailing throughout one test was 25 miles per hour; during all the others it was less than 20 miles per hour.

The tests were made upon well-constructed and well-maintained main-line track, 94 per cent of which is laid with 85-lb. rail, the remainder being laid with 75-lb. rail. Except through station grounds, where screenings or cinders are used for ballast, the track is full ballasted with broken stone.

5. *Conclusions.*—The results of the tests are presented in Fig. 10 and 11, pp. 31 and 33, in Table 3 on p. 35, and in the equations on p. 34. The curves, the table, and equations are each different expressions of the same facts. It is believed that by their use the probable total resistance of *entire* freight trains at various speeds may safely be predicted, when running upon straight and level track of good construction, during weather when the temperature is above 30° F., and the wind velocity is not more than 20 miles per hour, provided the *average* weight of the cars composing the train be known.

The results are applicable to trains of all varieties of make-up to be met with in service. They may be applied, without incurring material error, to trains which are homogeneous and to those which are mixed as regards individual car weight.

The results are primarily applicable to trains which have been in motion for some time. When trains are first started from yards, or after stops on the road of more than about 20 minutes' duration, their resistance is likely to be appreciably greater than is indicated by the results here presented. In rating locomotives, no consideration need be given this matter, except in determining "dead" ratings for low speeds, and then only when the ruling grade is located within six or seven miles of the starting point or of a regular road stop.

It is to be expected that some trains to be met with in service will have a resistance about 9 per cent in excess of that indicated by Fig. 10 and 11, due to variations in make-up or in external conditions within the limits to which the tests apply. If operating conditions make it essential to reduce to a minimum the risk of failure to haul the allotted tonnage, then this 9 per cent allowance should be made. This consideration, like the one preceding, is important only in rating locomotives for speeds under 15 miles per hour. At higher speeds, the occasional excess in the resistance of individual trains will result in nothing more serious than a slight increase in running time. It should be emphasized that this allowance, if made, is to be added to the resistance on level track—not to the gross resistance on grades.

III. The Methods and Means Employed in Conducting the Tests

6. The tests were carried on by means of the dynamometer car referred to as Test Car No. 17, which, when not in use, is held at Champaign, a district terminus. The car was operated from time to time in the regular trains leaving this point, and the trains selected were partly in the northbound, partly in the southbound traffic.

The plan was to determine, for each of the trains experimented upon, the relation of its resistance to its speed. This information was to be expressed finally as a resistance-speed curve such as is shown in Fig. 1 and in the various figures given in Appendix 5. The trains were so selected that their average car weights would vary throughout as great a range as possible. As will later appear, this range proved to be from the weight of an empty gondola to that of a fully loaded car of 100 000 lb. capacity. It was the expectation that when the resistance-speed curves of the individual tests were brought together, their analysis would reveal the relations existing between train resistance and car weight.

7. During each test the following information was obtained:

(*a*) The drawbar pull of the locomotive upon the train.

(*b*) The train speed.

(*c*) A continuous record of the time elapsed from the beginning of the test.

(*d*) The pressure existing in the brake cylinder of the test car.

(*e*) The direction of the wind relative to the direction of motion of the car.

(*f*) The velocity of the wind relative to the car.

(*g*) A record of the location of the test car upon the road.

(*h*) Air temperatures and other weather conditions.

(*i*) Data concerning the train, such as its weight, etc.

The information cited under items (*a*) to (*g*) was obtained in the form of continuous graphical records upon the chart which is produced by the apparatus of the dynamometer car. By means of this chart any of the quantities mentioned may be determined at any point upon the road.

The curves of draw-bar pull and speed provide the information essential to the investigation. Supplemented by an accurate profile and a record of train weight, they enable net train resistance to be calculated at any position of the train upon the road. The time record provides a means of calibrating and checking the speed curve. The pressure in the brake cylinder was recorded merely to make it possible to distinguish those periods during the test when the brakes were applied to the train; it being obviously necessary to ignore such portions of the record when making the calculations. The relative wind velocity and relative wind direction were obtained by means of an anemometer and a wind vane mounted on the roof of the test car. When compounded with the known speed and direction of motion of the car, these data permit the determination of the actual wind direction and wind velocity with respect to the track. In Appendix 5, for each test, there are recorded this actual wind velocity and actual wind direction with respect to the track for each point at which train resistance was determined. It is probable that these wind data are, under some circumstances, subject to a considerable error. Considering the length of the run made with each train and the length of time it was on the road, it is believed that the wind data thus obtained are, nevertheless, more reliable than those which might have been recorded by stationary instruments located at one or two points along the track. Item (*g*), the location of the car upon the road, was defined by marking upon the test car record the position of mile posts and stations at the moment they passed the car. By means of this record, it is possible to correlate any position of the train with the road profile. Data concerning the train were obtained by one or two observers who had no other duties. With the one exception noted beyond, all trains were weighed, to determine their tonnage. In addition to its weight, there was recorded for each train, its length[1], and for each car, its number, kind, stenciled "light weight", gross weight, capacity, and the initials of the owning road.

All test car instruments were calibrated before the tests, and their calibrations were frequently checked during the progress of the investigation. All observers were men experienced in the operation of the test car and many of them had participated also in the work of calculation and were consequently aware of the points at which alertness and care were especially needed. No effort has been spared, in conducting the tests, to insure accuracy in the data. These facts are here mentioned as having some significance to any one who may undertake to estimate the reliability of the results. Appendix 1 contains an illustration of one of the test car charts and a detailed description of the car itself.

This report includes the data and results from tests of 32 different trains. For the purposes of this research, tests were made of twelve other freight trains; but their results were finally excluded from the report. Three of these additional tests were rejected because of uncertainty about the train weights; one, because of a break-down in the test car recording apparatus during the progress of the test; and eight were disregarded because the temperatures prevailing were below the range for which it was intended the results should apply, the low temperature in some cases being coupled with high wind.

IV. Test Conditions and Train Data

8. *The Trains Tested.*—The test trains were all of such make-up as naturally resulted from the traffic conditions in the Champaign yards. For most of the tests the test car was simply coupled into the trains selected by the trainmaster, solely with reference to his convenience in operating and in returning the test car. As the investigation progressed, it became apparent that the accumulated data left certain gaps in the range of average car weights. There were at this stage, for example, few trains experimented upon with average car weights near 25 to 30 tons, and none with an average car weight of 70 tons. The last six or eight

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[1] Train length was determined by counting, during the test, the number of rail lengths corresponding to the length of the train and multiplying this number by 30 feet, which is the rail length for this track.

trains were therefore made up especially to supplement the data at these points. It should be understood, however, that nothing in this process resulted in a train make-up which was in any respect unusual. All the trains tested are, therefore, such as one might expect to find upon any road where the traffic conditions are normal. They include trains made up almost entirely of empty gondolas[1], others with considerable variation in both load per car and kind of car, and still others composed almost entirely of loaded box cars or of loaded gondolas.

Test S-1018 demands special mention in this connection. The train for this test included Illinois Central Railroad locomotives No. 423 and No. 732, weighing respectively 145 200 and 223 600 lb. Their combined weight constituted 13.6 per cent of the total train weight. These locomotives with their tenders were being hauled "dead" and had the main rods disconnected, as is usual in such cases. The first is of the 2-6-0 type, the second of the 2-8-0 type, and they and their tenders had therefore together 17 axles in operation. For the purpose of determining the average car weight for this train, these two locomotives were assumed to be equivalent, in their resistance, to a number of cars having a like number of axles, i. e., $4\frac{1}{4}$ cars. The results of the calculations warrant the belief that this view of the situation has resulted in no material error. A study of Table 1 will make clear the diversity in the composition of the trains.

All trains except No. S-1016, S-1018, S-1030A, and S-1030B were weighed upon one of the two track scales at Champaign. This weighing was done in the usual manner, by pulling the train over the scales and weighing the cars successively without uncoupling them. These track scales were in good condition and were each inspected four times during the test period. These inspections disclosed a maximum error in one scale of—$\frac{1}{5}$ per cent, in the other of—$\frac{1}{2}$per cent. The train in test S-1016, composed entirely of empty cars, by an error in arrangements, left the yards without being weighed. The weights stenciled on the cars were accepted as correct in this case. The train in test S-1018 was weighed upon track scales in the Chicago yards; and the trains of tests S-1030A and 1030B were weighed in the yards at Centralia. In test S-1021, after leaving the yards, two cars were added to the train, for which the weights were determined from the stenciled weights and the way-bills. In tests S-1030B and S-1048 the weights of one and two cars respectively were similarly determined, and in test S-1061 the stenciled weight was used for one empty car. Obviously no important errors in the total tonnage have resulted from possible inaccuracies in the weights of these cars.

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[1] In all parts of the report except Appendix 2, cars are designated as box, stock, gondola, flat, and tank cars. The term box car is made to include refrigerator cars, the test car and the caboose. The term gondola includes all unroofed cars with sides, such as coal cars, hopper cars, etc. In the tonnage records in Appendix 2, further distinctions are made.

All cars of all trains were of course provided with the usual four-wheeled truck. Presumably the majority of the cars had journals conforming to the specifications of the Master Car Builders' Association, which for some years have required that freight car journals be either 3¾ in. by 7 in., 4¼ in. by 8 in., 5 in. by 9 in. or 5½ in. by 10 in. in size, depending upon the car capacity. It is safe to assume that all trucks were provided with wheels of 33-in. standard diameter.

Throughout each test, observations were repeatedly made to discover such irregularities as hot journal boxes, brakes which were not free from the wheels, and trucks which did not freely follow the track. Such things occurred to the usual extent; a hot-box or two or an unreleased brake being occasionally found on some of the trains, while others were entirely free from such defects. The record of such matters was given consideration in making the calculations; but, as was anticipated, the results showed no discrepancies which could be explained by such causes.

The range over which the train data for all of the tests varied is as follows:

	Minimum	Maximum
Total train weight, tons	747	2908
Average weight of cars composing the train, tons	16.12	69.92
No. of cars in the train	26	89
Train length, feet	1120	3480

Complete information concerning each train is given in Appendix 2.

9. *The Track.*—The track upon which the experiments were carried on extends from Gilman to Mattoon, Illinois, a distance of 91 miles, and lies upon the Chicago division of the main line of the Illinois Central Railroad. Until about ten years ago this was a single track road, and one of the oldest in the State. At that time a second track was constructed, and the roadbed for both tracks is now well settled and in good condition. The maxi-

TABLE 1

A SUMMARY OF TEST CONDITIONS AND TRAIN DATA

Test No.	Test Date	Weather Conditions						Train Data										
Laboratory Serial No.			Air Temperature Degrees F.		Average Approximate Wind Velocity miles per hour	Range of the Direction of the Wind with Respect to the Track		Train Length, feet	Weights		Total Number of Cars in the Train	Train Make-Up						
												Conditions of Loading			Kind of Cars—In Percentages of the Total Number of Cars			
			At Beginning of Test	At End of Test		From	To		Gross Train Weight tons	Average Gross Weight Per Car tons		Number of Empty Cars	Number of Loaded Cars	Loaded Cars in Percentage of Total Number	Box Cars per cent	Gondola Cars per cent	Flat Cars per cent	Tank Cars per cent
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
S-1013	4-27-08	Wet	42	44	19	+35°L	90°L	2784	2549	38.04	67	10	57	85	82	13	0	5
S-1015	4-29-08	Fair	40	48	10	+25°L	—80°L	2520	2489	36.08	69	8	61	88	68	6	16	10
S-1016	4-30-08	ʻʻ	44	48	10	+15°R	+60°R	3030	1161	16.12	72	72	0	0	3	97	0	0
S-1017	5- 1-08	Wet	48	54	16	+45°L	—80°L	2670	2532	38.44	66	13	53	80	95	5	0	0
S-1018	5- 2-08	Fair	40	45	11	+10°R	+85°R	2130	1353	25.40*	49*	34	15	31	61	6	16	17
S-1019	5- 9-08	ʻʻ	44	62	25	+20°R	+45°R	3480	1572	17.72	89	75	14	16	34	58	7	1
S-1021	5-13-08	Wet	66	70	17	+60°R	+80°R	2400	2908	46.16	63	10	53	84	32	60	5	3
S-1023	5-23-08	Fair	62	74	17	+75°R	—80°R	2320	2243	38.72	58	17	41	71	45	52	0	3
S-1027	7- 2-08	Wet	64	80	14	—50°R	+70°R	1710	2185	47.44	46	3	43	94	22	76	2	0
S-1030A	7- 8-08	Fair	60	68	6	+20°R	+65°R	1380	2036	59.88	34	2	32	94	6	94	0	0
S-1030B	7- 8-08	ʻʻ	68	72	7	+20°R	+65°R	1650	2342	57.12	41	3	38	93	20	80	0	0
S-1031	7-22-08	ʻʻ	70	82	5	+ 0°	+40°L	1425	747	20.72	36	30	6	17	94	3	3	0
S-1033	9-26-08	ʻʻ	66	82	12	+ 5°L	+15°R	1710	2275	51.70	44	2	42	95	5	95	0	0
S-1034	10-3-08	ʻʻ	42	60	4	— 0°	+85°L	3015	1259	16.56	76	76	0	0	1	99	0	0
S-1036	10-10-08	ʻʻ	40	62	6	+15°R	—15°R	2010	1961	37.72	52	8	44	85	73	25	2	0
S-1038	10-15-08	ʻʻ	58	72	16	+ 5°L	+25°L	1650	2144	52.28	41	3	38	93	22	78	0	0
S-1040	10-24-08	Wet	57	53	11	+15°R	+40°R	1830	2152	45.76	47	2	45	96	49	49	0	2
S-1043	11-7-08	Fair	38	53	8	+ 5°R	+65°R	2580	1118	16.92	66	65	1	2	24	74	0	2
S-1048	11-28-08	ʻʻ	36	39	6	+ 5°R	+30°L	a2175	2443	45.21	54	8	46	85	37	63	0	0
								b2100	2355	45.24	52	8	44	85	38	62	0	0
S-1050	1-23-09	ʻʻ	53	66	8	+ 0°	—25°R	1620	1618	40.44	40	16	24	60	75	25	0	0

S-1052	1-28-09	Wet	36	40	11	−45°L	+70°L	2430	1514	24.80	61	44	17	28	61	38	1	0
S-1057	3- 6-09	Fair	34	40	10	+20°R	−35°L	1830	2107	41.32	51	8	43	84	49	43	6	2
S-1061	3-13-09	"	41	38	7	+45°L	−85°L	1785	2252	51.20	44	3	41	93	5	84	11	0
S-1063	3-19-09	Wet	39	40	12	+20°R	+40°R	3060	1484	20.04	74	70	4	5	7	93	0	0
S-1070	4-17-09	Fair	58	71	4	+ 0°	−65°L	2400	1622	24.60	66	49	17	26	58*	42	0	0
S-1072	5- 1-09	"	35	37	17	+70°L	90°L	1200	1859	66.40	28	1	27	96	4	96	0	0
S-1073	5- 4-09	"	53	63	10	+25°L	+70°R	1200	1880	67.16	28	1	27	96	4	96	0	0
S-1074	5- 7-09	"	45	60	10	+65°L	−80°L	3180	1340	16.56	81	81	0	0	2	98	0	0
S-1076	5-11-09	"	51	67	16	+40°R	+75°R	1120	1818	69.92	26	1	25	96	4	96	0	0
S-1077	5-14-09	"	64	70	13	−25°R	−75°R	2145	1505	28.40	53	35	18	34	74	26	0	0
S-1079	5-18-09	"	65	68	18	+65°R	−85°R	2070	1685	33.04	51	14	37	73	90	10	0	0
S-1080	5-21-09	"	50	70	11	+ 0°	+45°L	2550	1347	21.40	63	57	6	10	16	84	0	0

Notes: 1. Columns 7 and 8—Direction is designated by the angle made with the track. A wind any component of whose velocity helps the train forward is marked +; winds with opposing velocity components are marked—. Winds from the right side of the track are designated as R, from the left side as L. Thus + 40°R means a wind blowing from the rear and from the right hand side, whose direction makes an angle of 40° with the track.

2 *Columns 11 and 12—Train has two "dead" locomotives and tenders in addition to cars noted.

3. *Column 16—includes 15 stock cars classed as box.

4. All data apply to the train only—engine and tender are excluded.

5. Columns 9 to 19: a.—from Champaign to Rantoul; b.—from Rantoul to Gilman.

mum grade against northbound traffic is 29 ft. per mile and against southbound traffic, 31.9 ft. per mile. In all the 91 miles there are only 7850 ft. of curved track.

Through station grounds the tracks are ballasted with screenings or cinders; all other portions of both tracks (about 83 of the 91 miles) are full ballasted with broken limestone. The cross-ties are of oak, laid 20 in. center to center. About 10¼ miles of the west track are laid with 75-lb. A. S. C. E rail, put down in 1894 and 1895; while the remainder of the west track and all of the east track are laid with 85-lb. A. S. C. E rails, the oldest of which was put down in 1900. During eight months of the year there is employed in maintaining this portion of the road a force of men which averages one man per mile of track; during the other four months this force is reduced to one man for each two miles. Further details concerning the track are given in Appendix 3. As regards both its construction and maintenance this track is such as one may expect to find upon the main lines of first-class railroads.

These 91 miles of track were especially surveyed, immediately preceding the tests, by the Railway Engineering Department of the University for the purposes of this and similar investigations. The levels were run on the east track and readings were taken to 0.1 ft. at stations 300 ft. apart; and turning points were taken at every fourth station where levels were read to 0.01 ft. The results of the survey are expressed in a profile drawn to a scale of ¼ in. to 100 ft., which was used in making the test calculations.

10. *The Weather Conditions.*—In Table 1 the weather prevailing during each test is designated as either fair or wet, wet weather meaning either continuous or intermittent rain. During 7 of the 32 tests the weather was wet. The lowest air temperature recorded at any time during any test is 34° F.; and the highest recorded temperature is 82° F.

The column headed "average wind velocity" in Table 1 presents the averages of the calculated wind velocities derived for each point or section of the test in question for which the train resistance was determined. An inspection of the tables in Appendix 5 shows a considerable variation between the wind velocities at different points during the same test. The approximate maximum average wind velocity prevailing during any test was 25 miles per hour; the minimum was 4 miles per hour. The actual wind direction (with respect to the track) varied during the tests, as would be expected, through the entire 360°. The tables in Appendix 5 show this direction for each point at which train resistance was computed; but it seems impossible to make any useful generalization of the data there presented.

It was intended to so select the tests that the weather conditions, the temperatures, and the wind velocities would be such as usually prevail in most parts of the country from the middle of spring until the middle of autumn when the basic or "summer" tonnage ratings are in force—such conditions, in short, as would give rise to no appreciable difficulties in train operation.

V. Methods Employed in Calculating the Results.

11. The immediate purpose in making the calculations was to produce for each test a curve showing the relation between resistance and speed, for as great a variety of speeds as the data would permit. This involves calculating the train resistance at various positions of the train upon the track, and the first step towards this end is the inspection of the test car record in order to select suitable points or sections at which the resistance may be calculated. The considerations of first importance in this selection are that the points represent finally as great a speed range as possible, and that the speeds be approximately evenly distributed within this range. Points and sections were selected only where the entire train was running and continued to run upon straight track; resistance due to track curvature is therefore entirely eliminated. The data essential to the process of calculation are the draw-bar pull of the engine, the train speed and its acceleration, the tonnage, and the profile. The pull and the speed, as previously stated, are determined from continuous curves drawn on the test car chart. Two processes have been used, designated here as Method 1 and Method 2. By Method 1, the momentary values of pull, speed, acceleration, and grade were determined for a particular position of the train upon the road; by Method 2 the average values of these quantities were determined for the period during which the test car was passing over a definite section of the track.

12. *Method 1: Resistance at a Point on the Road.*—The point having been chosen, the pull and the speed were found by direct

readings from the chart. This pull divided by the tonnage gives the gross train resistance at this speed, and this gross resistance was next corrected for both acceleration and grade resistances. The acceleration was determined by graphical methods from the speed curve, and the grade was found by correlating the train's position with the profile. The points were all so selected that at the moment under consideration, the entire train was on a nearly uniform grade. Method 1 results in momentary values of train resistance at the points considered.

13. *Method 2: Average Resistance Over a Section.*—By this method the average value of train resistance was determined for the period during which the test car at the head of the train was passing a selected section of the track. This track section corresponds to a certain length or section on the test car record. It was so selected that the speed of the car when entering was nearly equal to its speed at exit, and further so that no considerable variations in speed occurred during transit over the section. The sections chosen have varied in length from about $\frac{1}{4}$ mile to 1 mile. The variations in speed in passing the section have generally amounted to less than 2.0 miles per hour, and the maximum variation over any selected section is 11.7 miles per hour. In only 58 cases out of a total of 560 does this speed variation exceed 5.0 miles per hour. These portions of the chart having been chosen, the average pull was next found by determining the average ordinate of the curve of draw-bar pull, and the average speed was found by means of the section length and the time record. Gross resistance in pounds per ton was next derived by dividing this value of pull by the tonnage, and this gross resistance was then corrected for the resistances due to acceleration and grade, as in Method 1.

In this case the average acceleration is found by consideration of the speeds at entrance to and exit from the section. In order to correct for grade, the elevation of the center of gravity[1] of the train was determined for that position of the train at which the test car entered the section, and again for the position at which the car left the section. The difference between these elevations establishes the effective average grade, which either helps or opposes the locomotive while the train passes the section. These elevations of the center of gravity of the train may not be determined with sufficient accuracy unless the train at the moment is on a practically uniform grade. The section limits were therefore so chosen.

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[1] The location in the train of its center of gravity was determined thus: Assume a train which weighs 1800 tons, is 2400 feet long, and is composed of 60 cars. By inspection of the tonnage record we find that one half of this weight (900 tons) lies in the first 25 cars. Hence the center of gravity is located $\frac{25}{60} \times 2400 = 1000$ ft. from the front end.

Method 2 results in a value of *average* train resistance for the *average* speed at which the train passes the section under consideration. It would be rigidly correct if train resistance varied uniformly with speed, in other words, if the curve showing the relation of resistance to speed were a straight line. This, of course, is not the case, and the process therefore gives results which are slightly in error. However, as stated above, the section was so chosen that the difference between the speeds at entrance to and exit from the section was small; and for the speed range represented by this difference, the curve of train resistance deviates but little from a straight line. Such error as does result from the process is, therefore, very small and is of no moment whatever when compared with variations, due to natural causes, which occur in the resistance itself.

14. *Comparison of the Two Methods.*—The two methods are fundamentally alike. Although the first is the less laborious, it requires the determination of acceleration at a point on the speed curve, which it is sometimes difficult to make accurately. For this reason the second method is generally preferable. Method 2 is also to be preferred because it deals with average values and therefore tends to eliminate from the results the incidental momentary variations which occur in the resistance itself. Consequently, the second method has been employed whenever possible, and the first method has been resorted to, as a rule, only in those cases where the limitations imposed in the selection of sections for Method 2 would have resulted in too few values from which to plot the resistance curves. Of all the individual resistance values incorporated in the report, only 32 per cent were determined by Method 1. The care exercised in the calculations, and a study of the plotted values obtained by both processes, seem to warrant the conclusion that their results are equally reliable. In Fig. 1 and in the figures in Appendix 5, the circles represent values derived by Method 1, and the circular black spots represent values obtained by Method 2.

15. *General Considerations.*—Even in freight train operation the tractive effort required to produce acceleration in the speed is frequently greater than that required to overcome all other resistances combined. To produce, for example, an acceleration of 0.1 mile per hour per second, requires a tractive effort of about 9 lb. per ton, in addition to that required by net train resistance and grade resistance. Since the acceleration resistance may constitute so large a proportion of the gross resistance, it is important that its determination be made with great care. This fact has been impressed upon all who were concerned with these tests. In calculating the acceleration resistance, both the force required to produce acceleration in the rotation of the wheels and axles, and the force required to produce the acceleration in the motion of translation of the train as a whole were determined.

The test car records make it possible to distinguish those portions of each test where the brakes were applied. Such places, few in number, were of course avoided in selecting points and sections for determining resistance. The records also show where hot-boxes and unreleased brakes were discovered in the train, and such defects were given consideration in making the calculations. They occurred infrequently and their effect could not be distinguished in the results. While therefore such portions of the record were avoided if convenient, sections and points on the charts, otherwise suitable for calculation, were not rejected on these accounts.

16. *The Effect of Stops in Limiting the Selection of Points and Sections.*—Early in the progess of this work, when low air temperatures were first encountered, it became apparent that when the train was first started from rest, its resistance, calculated for a number of points at which the speed was the same, was occasionally unusually high. This was true not only for those portions of the run made immediately after leaving the yards; but also for those portions immediately following stops on the road. In a certain test, for example, the values of net resistance, calculated at various points, at all of which the speed was 20 miles per hour, varied between 6.8 lb. and 5 lb. per ton—a difference of 27 per cent—for points selected within the first 9 miles of the run; whereas values of resistance at the same speed, determined later in the test, differed by only 10 per cent. The air tem-

perature during this test (not included in the report) varied between 22° and 26°.

For a number of tests such resistance values were plotted with respect to the distances from the yards of the points to which they apply. This process disclosed a surprisingly regular decrease in the resistance until a distance of approximately ten miles was reached, after which the resistance had settled down to a fairly uniform value. Similar variations were found to occur to some extent during tests when the air temperature was as high as 50° or 60°. This study[1] led to the conclusion that this difference in resistance was due to variations in the conditions of lubrication of the car journals, and that such variations were chiefly caused by changes in journal temperature. All this is, of course, in accord with the common belief of those experienced in train operation. The reason for discussing it in this place is that the facts stated have influenced the procedure in making calculations for this series of tests.

Since the variations in resistance are so great during the early part of the run, no point or section has been selected for calculation within about the first ten miles of any test. If other points or sections, located farther from the start, were near stops, such points were rejected unless further investigation proved that at these places the train resistance had become nearly uniform in value. Fortunately, the operating conditions were such as to entail few stops on the road, and the selection of points and sections for the calculations has not been unduly limited on these accounts[2].

The effect of these limitations is to make the results of this investigation primarily applicable to trains which have been in motion for some time. Since, however, stops are not usually made upon ruling grades,and since if stops are made at other places on the road, the locomotive has available tractive power in excess of the requirements, the results of these tests are generally applicable in the solution of tonnage rating problems, except where the ruling grade occurs near a yard or other point where the trains are made up. In such cases the tonnage determined from the resistance curves here presented may prove to be somewhat too great.

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[1] Further investigation of this matter is in progress, and the results will probably be published soon.

[2] During the 32 tests included in the investigation only 68 stops, all told, were made after leaving the yards. Of these, one was of 55 minutes duration, nine lasted between 20 and 40 minutes, twenty-two between 10 and 20 minutes, and thirty-six less than 10 minutes.

17. *The Derivation of the Resistance Curves.*—The calculations result, for each test, in a series of values of net train resistance at a variety of speeds. These values of resistance were plotted with respect to speed, and gave such a diagram as in Fig. 1.

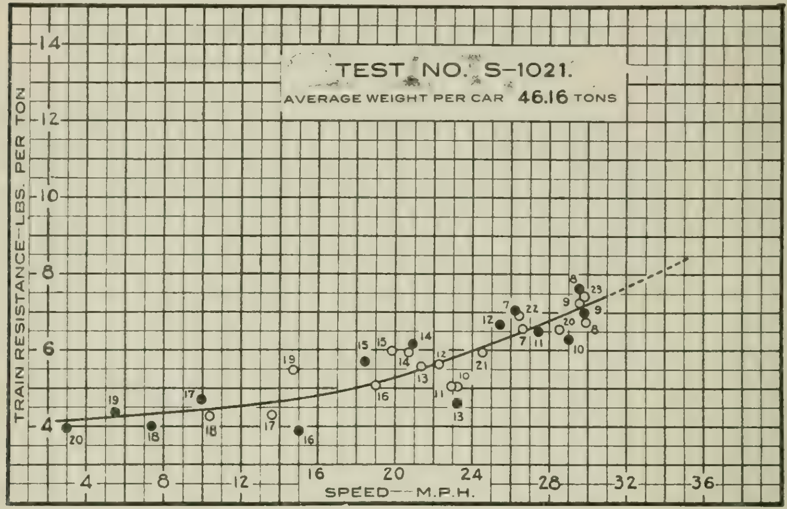

FIG. 1 THE RELATION OF RESISTANCE TO SPEED FOR TEST S-1021

The curve, such as is shown there, was next drawn to express, for the test in question, the relation existing between resistance and speed. In order to draw this curve, the plotted points were assumed to be arranged in a number of groups, and for each group the averages of the values of speed and of resistance were determined. By these averages a new point or "center of gravity" of the group was then plotted. The curve was drawn by confining attention to the few points thus determined. The groups of points were arbitrarily selected so that the resulting "centers of gravity" would be distributed nearly equidistantly throughout the speed range. All curves presented in the report, except those exhibited in Fig. 11, were drawn by this process.

All reasonable precautions have been taken to attain accuracy in the calculations. In determining each value of resistance, each step in the process was duplicated at a different time and generally by a different person. The transcription of all tables, the plotting of points and the drawing of curves have been similarly checked.

VI. THE RESULTS OF THE TESTS

18. *Results of the Individual Tests.*—The immediate result of each test is a curve which shows for the train under consideration the relation existing between train resistance and speed. Fig. 1 is such a curve derived from test S-1021; similar curves for the other tests are exhibited in Appendix 5. Fig. 1 is fairly representative of the entire group of curves, and such discussion of it as follows is general in its application.

The plotted points[1] show unmistakably an increase in resistance as the speed increases, and the curve drawn represents the mean relation between resistance and speed. In Fig. 1 the maximum variation from this mean of any calculated value of resistance is about 20 per cent; the next largest variation is 16 per cent and other calculated values of resistance differ from the values determined from the curve by generally less than 10 per cent. In a majority of the tests the maximum variation is less than in Fig. 1, and the general agreement between the calculated values of resistance and the ordinates of the curve is better than in the test chosen for illustration.

It has been thought desirable to express more specifically this variation between the calculated values of resistance and the mean values as derived from the curves drawn. To this end, for all tests, all calculated values of resistance for speeds between 8 and 12 miles per hour were compared with the ordinates of the curves at the corresponding speeds and the percentage difference was determined in each case. These percentages were then arranged in two groups and averaged. The one group included the results from all points lying above the curve, the other from those lying below it. The whole process was next repeated for speeds between 28 and 32 miles per hour. The results are as follows:—

AVERAGE DEVIATION (FOR ALL TESTS) OF CALCULATED RESISTANCE FROM THE MEAN VALUES DERIVED FROM THE CURVES—EXPRESSED IN PERCENTAGE OF THE MEAN VALUES.

Speed	Above the Mean	Below the Mean
8 to 12 m. p. h.	6.4 per cent	7.6 per cent
28 to 32 m. p. h.	5.6 per cent	6.6 per cent

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[1] The numbers shown near the points are the item numbers of the tables in Appendix 5. The tables exhibit the calculated values of resistance and speed, which are the co-ordinates of the plotted points.

Such variation seems not unduly great for this class of experimental work.

These differences may be due in part to accumulated errors in instruments or in the calculations. In all cases, however, where the calculated value of resistance varied by an unusual amount from the mean, all calculations leading thereto were repeated a second time and errors thus discovered have been eliminated from the report. The explanation for such differences need not be sought further than in the variations which actually occur from time to time, in the resistance itself. Variations in such components of train resistance as flange friction and wind resistance are probably sufficiently great to account for the differences discussed above. The data do not permit the influences of such components of resistance to be differentiated.

The curve drawn for each test has been accepted as representing the average values of net train resistance with a degree of accuracy sufficient for the purpose of rating locomotives. Such temporary excess of resistance as may be expected to occur will generally be absorbed in that reserve in the tractive effort of the locomotive which must be allowed in any system of tonnage rating.

19. *Results of All the Tests.*—The resistance curves for the individual tests have all been brought together on one sheet, a reproduction of which is shown as Fig. 2. The curves there drawn are duplicates of those separately shown in Appendix 5[1]. Fig. 2 displays the immediate results of the whole research. The lower curves give values of resistance varying from 3 lb. to 5½ lb. per ton, while the upper curves show resistance values varying from 7 lb. to 14 lb. per ton. Resistance values at the lower speeds differ by 100 per cent, and values at higher speeds differ by as much as 200 per cent. If further analysis had not revealed the cause of the great variation in resistance here shown, Fig. 2 would have remained a useless exhibit.

The explanation of this variation has been sought in the test conditions enumerated below, each of which, it was conceived, might have contributed in some degree to bring about the differences disclosed in Fig. 2:

(*a*) Weather and temperature conditions.

(*b*) Wind velocity and direction.

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[1] The numbers shown on the curves are the last two figures of the test numbers. The curve marked 43 is derived from test S-1043.

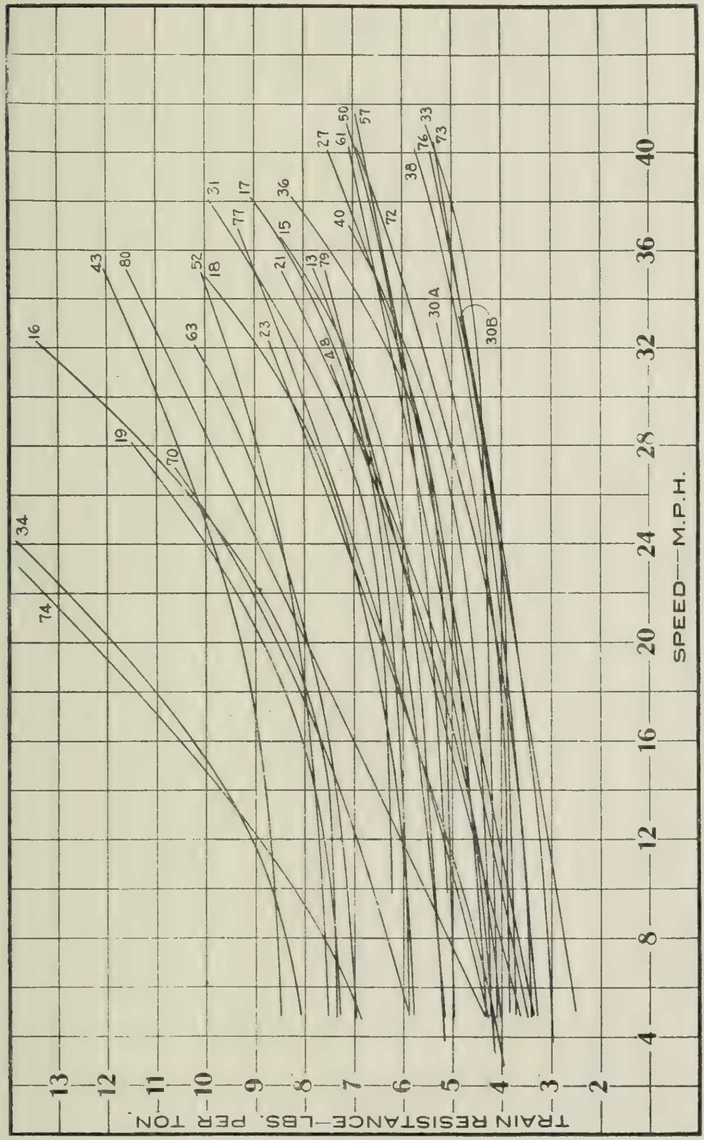

FIG. 2 CURVES SHOWING THE RELATION BETWEEN RESISTANCE AND SPEED FOR EACH OF THE TESTS

(*c*) Kind of cars composing the train.

(*d*) Position of the loaded cars in the train.

(*e*) Defects in train equipment.

(*f*) Average weight of the cars in the train.

The first five conditions are either uncontrollable or were purposely not controlled during these experiments. Attempts to explain the differences between the curves of Fig. 2 by reference to one or the other of these five factors have been altogether unsuccessful. While it is true that difference in wind velocity, for example, might be accepted as a plausible explanation of the differences between two or three curves selected at random from Fig. 2, such explanation will not hold when applied to two or three other curves similarly chosen; and it fails altogether to explain such differences when it is applied to the whole group. The same remarks apply to attempts to explain the differences between the curves of Fig. 2 by referring them to any other of the first five items cited above.

Item *f*, however, has furnished the clue whereby the apparent confusion in the results of the tests, as exhibited in Fig. 2, has been explained. It may be stated at once that the difference in train resistance for various tests is believed to be due chiefly to differences in the average gross car weights existing during the tests. An explanation of the process which led to this opinton follows immediately below. As was stated at the outset, this conclusion was anticipated when the work was begun, and the average car weight was therefore controlled during the experiments, and made to vary through the widest possible range.

20. *The Effects of Car Weight on Resistance.*—The four upper curves of Fig. 2 are derived from trains in which the average weight per car was about 16 or 17 tons. The lowest curves are those derived from trains in which the car weight was nearly 70 tons. These facts serve as a rough indication of the part played by car weight in effecting changes in train resistance. This influence is more definitely brought out in the following discussion.

If from each of the curves of Fig. 2 the value of resistance is determined at one speed, say 5 miles per hour, these values of resistance may then be plotted with respect to their corresponding values of car weight; and, since the speed is common, its influence is eliminated and the resulting diagram may be expected to reveal the relation existing between train resistance and average weight per car. Table 2 was prepared to facilitate this process. In it the tests are arranged in the order of the average car weights. These weights are given in the second column and in the succeeding columns are set down the resistance values obtained from the *curves* of the individual tests, for each of seven different speeds. Table 2 therefore presents the values of the coordinates of seven points on each of the curves of Fig. 2 and hence, like Fig. 2, summarizes the immediate results of all tests[1].

TABLE 2 VALUES OF RESISTANCE AT VARIOUS SPEEDS, DERIVED FROM THE CURVES FOR THE INDIVIDUAL TESTS. THIS TABLE PROVIDES THE CO-ORDINATES OF THE POINTS PLOTTED IN FIG. 3 TO 9.

Test No.	Aver. Weight per Car tons.	Train Resistance—pounds per ton.						
		5 m. p. h.	10 m. p. h.	15 m. p. h.	20 m. p. h.	25 m. p. h.	30 m. p. h.	35 m. p. h.
S-1016	16.12	7.35	7.40	7.62	8.37	9.91	12.22	
S-1034	16.56	8.10	8.70	9.92	11.90	14.30		
S-1074	16.56	6.92	8.23	10.10	12.32	14.70		
S-1043	16.92	8.50	8.61	8.85	9.30	10.00	10.95	12.04
S-1019	17.72	7.30	7.47	7.90	8.85	10.32		
S-1063	20.04	6.98	7.13	7.43	7.90	8.63	9.63	
S-1031	20.72		6.24	6.30	6.40	6.73	7.60	8.94
S-1080	21.40	4.40	5.57	6.75	7.94	9.15	10.35	11.55
S-1070	24.60	5.93	6.63	7.47	8.57	9.90		
S-1052	24.80	7.55	7.63	7.80	8.10	8.55	9.20	10.05
S-1018	25.40	5.80	5.95	6.20	6.63	7.22	8.26	10.02
S-1077	28.40	4.32	4.91	5.58	6.34	7.15	8.01	8.96
S-1079	33.04	3.66	4.30	4.92	5.60	6.22	6.89	7.55
S-1015	36.08	5.20	5.36	5.52	5.70	6.02	6.71	7.95
S-1036	37.72	4.98	5.03	5.12	5.15	5.31	5.88	7.15
S-1013	38.04		5.40	5.65	5.95	6.32	6.90	7.68
S-1017	38.44	5.90	5.95	6.02	6.20	6.48	7.01	8.03
S-1023	38.72	4.16	4.80	5.56	6.40	7.30	8.25	
S-1050	40.44		5.10	5.25	5.40	5.62	5.90	6.33
S-1057	41.32	3.40	3.88	4.35	4.83	5.31	5.80	6.30
S-1048	45.24	4.05	4.35	4.80	5.48	6.30	7.23	
S-1040	45.76	4.22	4.30	4.40	4.58	4.90	5.52	6.53
S-1021	46.16	4.21	4.41	4.72	5.29	6.15	7.20	8.40
S-1027	47.44	4.31	4.48	4.67	4.90	5.22	5.79	6.55
S-1061	51.20	3.50	4.00	4.51	5.01	5.51	6.01	6.53
S 1033	51.72	4.10	4.15	4.20	4.25	4.32	4.40	4.65
S-1038	52 28	3.30	3.50	3.71	3.95	4.25	4.60	5.08
S-1030B	57.12	3.73	3.80	3.82	3.90	4.10	4.50	
S-1030A	59.88	3.84	3.88	3.92	4.10	4.45	4.95	
S-1072	66.40	3.40	3.50	3.70	4.10	4.61	5.27	6.00
S-1073	67.16	2.52	2.90	3.30	3.70	4.10	4.50	4.90
S-1076	69.92	2.97	3.13	3.37	3.70	4.04	4.49	4.95

In Table 2 the second and third columns present a series of values of average car weight and of train resistance at 5 miles per hour. Each pair of these values represents the results of one of the 32 tests. Using these pairs of values as coordinates, a series of points has been plotted to form a new diagram, Fig. 3, For example, the point marked 21 in Fig. 3 is derived from the curve of test S-1021. The curve of resistance for this test (see Fig. 1 or Fig. 2) shows that at 5 miles per hour the mean resistance is 4.21 lb. per ton. During this test the average weight of the cars in the train was 46.16 tons. Table 2 also exhibits both of these values which, when plotted in Fig. 3, determine the point there marked 21. The other points of Fig. 3 were similarly determined. Each point represents the value of resistance at 5 miles per hour derived from a particular test train.

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[1] Table 2 has been prepared from the original curves of the individual tests, only one of which is separately presented in Part I (see Fig. 1). It gives no information not obtainable from Fig. 2, but presents the information in more convenient form, since the number of curves drawn in the figure makes it confusing.

Although there is considerable variation among the points of Fig. 3, they indicate clearly a decrease in the resistance as the car weight increases. The curve drawn in Fig. 3 represents, for the trains tested, the mean relation which existed between resistance at 5 miles per hour and the average car weight[1]. For higher speeds this relation between resistance and car weight is shown by Fig. 4 to 9, which were derived by the same methods employed in producing Fig. 3.

The variation in resistance represented by the points in Fig. 3 to 9 is sufficient to warrant further discussion. Such discussion will, however, be postponed until later in the report. The conclusion reached is that these variations are largely caused by factors which are uncontrollable in ordinary train operation. If this be admitted, it is clear that the discussion of such variations may enter into the solution of tonnage rating problems only as an argument for reserve tractive effort in the locomotive. An estimate of the desirable amount of such reserve appears beyond.

The curves of Fig. 3 to 9 have been accepted as representing, for these tests, the mean relation which existed between train resistance and the average gross weight of the cars composing the trains. These curves exhibit this relation at seven different speeds, 5, 10, 15, 20, 25, 30 and 35 miles per hour. For convenience in use and to make comparison easier, these seven curves have been brought together in one diagram which is reproduced in Fig. 10.

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[1] As has been previously explained, the curve is drawn by finding the "centers of gravity" of several groups of points These centers are defined in Fig. 3 to 9 by the crosses within circles. Points 34 and 74 were virtually ignored in drawing the curves of Fig. 6 and 7. The numbers at the points are the last two figures of the test numbers.

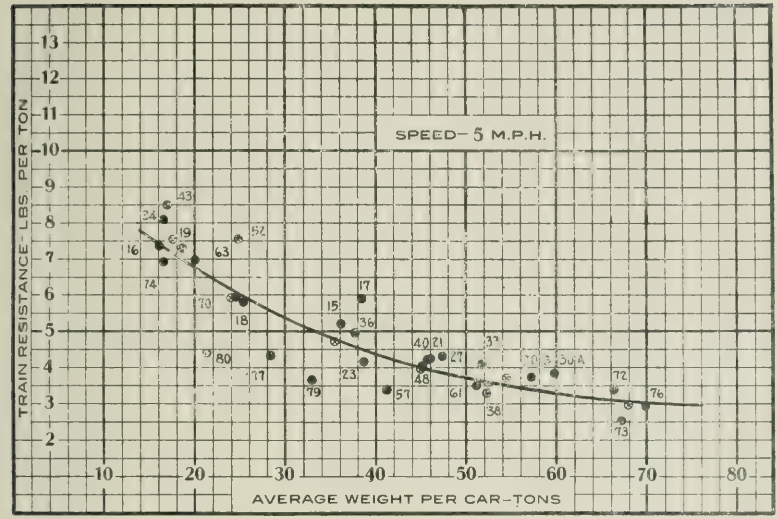

FIG. 3 THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 5 MILES PER HOUR

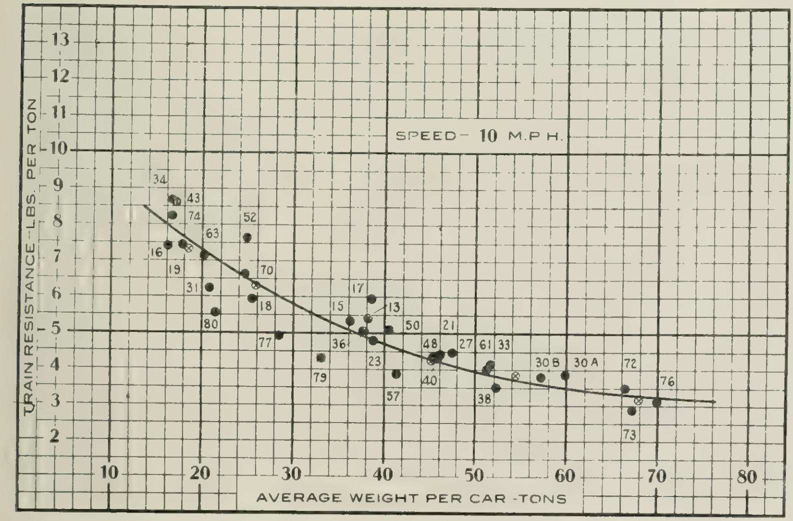

FIG. 4 THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 10 MILES PER HOUR

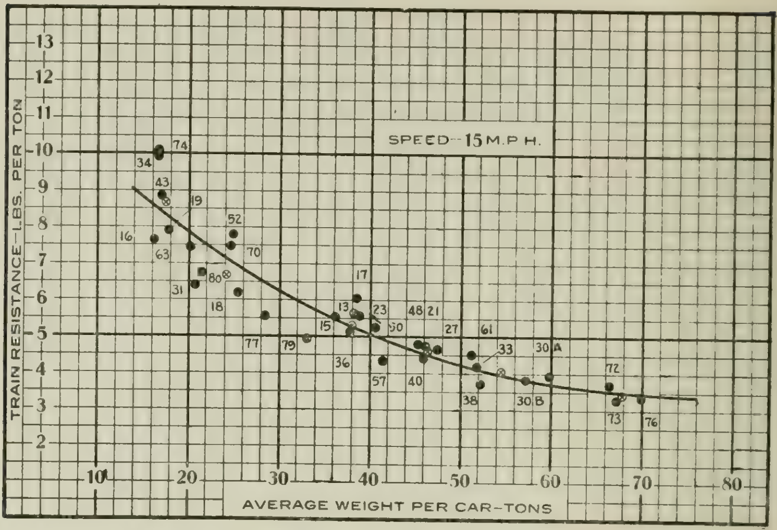

Fig. 5 The Relation Between Resistance and Average Car Weight, at a Speed of 15 Miles per Hour

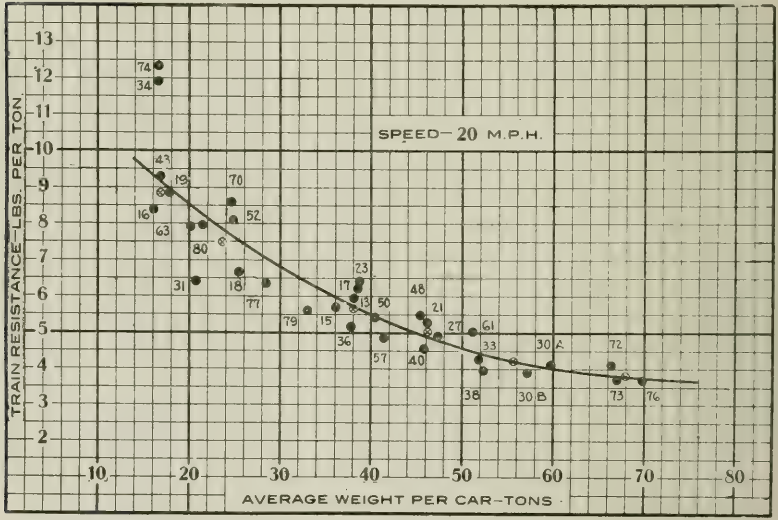

Fig. 6 The Relation Between Resistance and Average Car Weight, at a Speed of 20 Miles per Hour

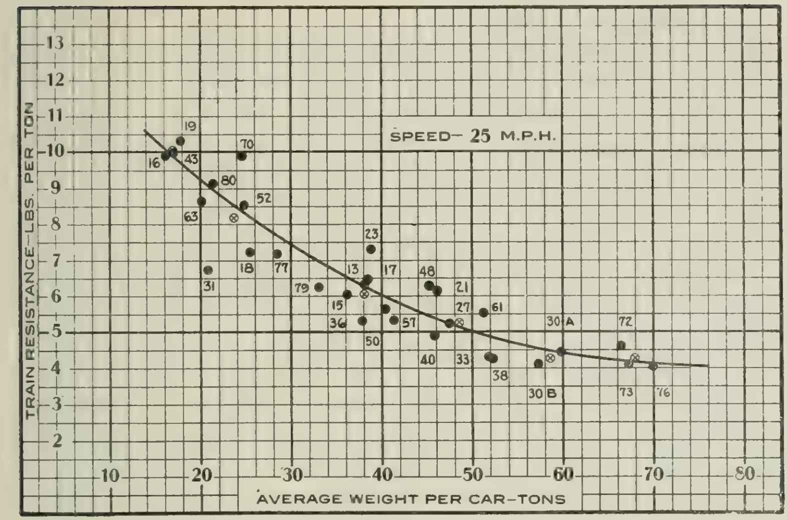

FIG. 7 THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 25 MILES PER HOUR

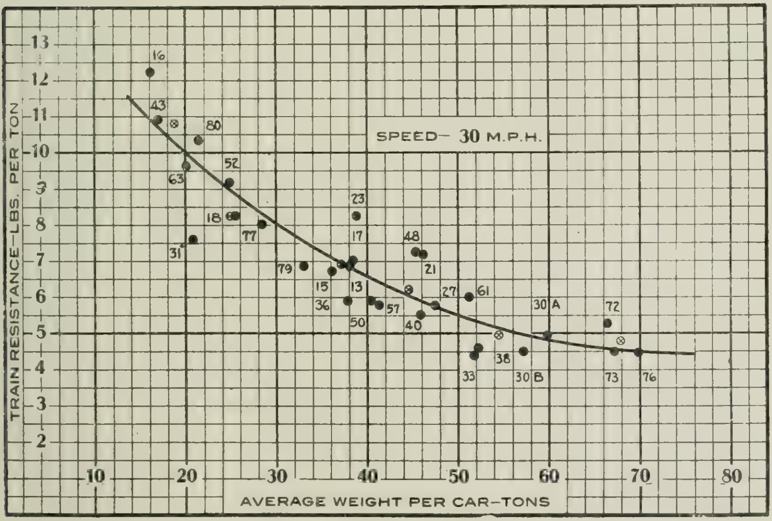

FIG. 8 THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 30 MILES PER HOUR

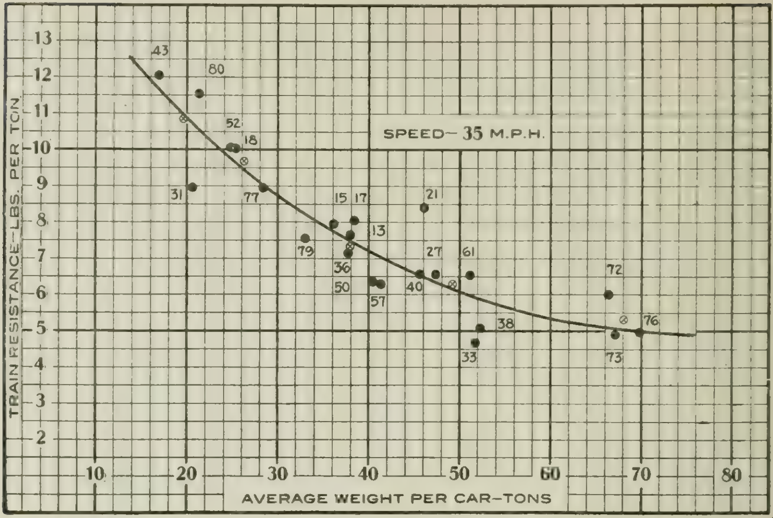

FIG. 9 THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 35 MILES PER HOUR

Fig. 10 presents the final results of the whole research. Each of the curves there drawn shows the mean relation, which existed during the tests, between car weight and resistance at a definite speed.

It is believed that the curves of Fig. 10 are generally applicable to ordinary American freight trains, provided the conditions surrounding their operation are like those which prevailed during these tests. The curves of Fig. 10 enable one to determine the probable mean resistance of any such train, at speeds between 5 and 35 miles per hour, provided the average weight of the cars composing the train be known.

21. *The Results Expressed as Resistance-Speed Curves.*—While Fig. 10 presents the main results of the experiments, the form in which these results are there expressed is unusual. Ordinarily, train resistance is expressed either as a curve or equation which defines the relation between resistance and speed, instead of the relation between resistance and car weight as in Fig. 10. Obviously, to express the results of these experiments in the usual form, a single curve will not suffice, since the influence of car weight cannot be thereby made evident. A number of curves will

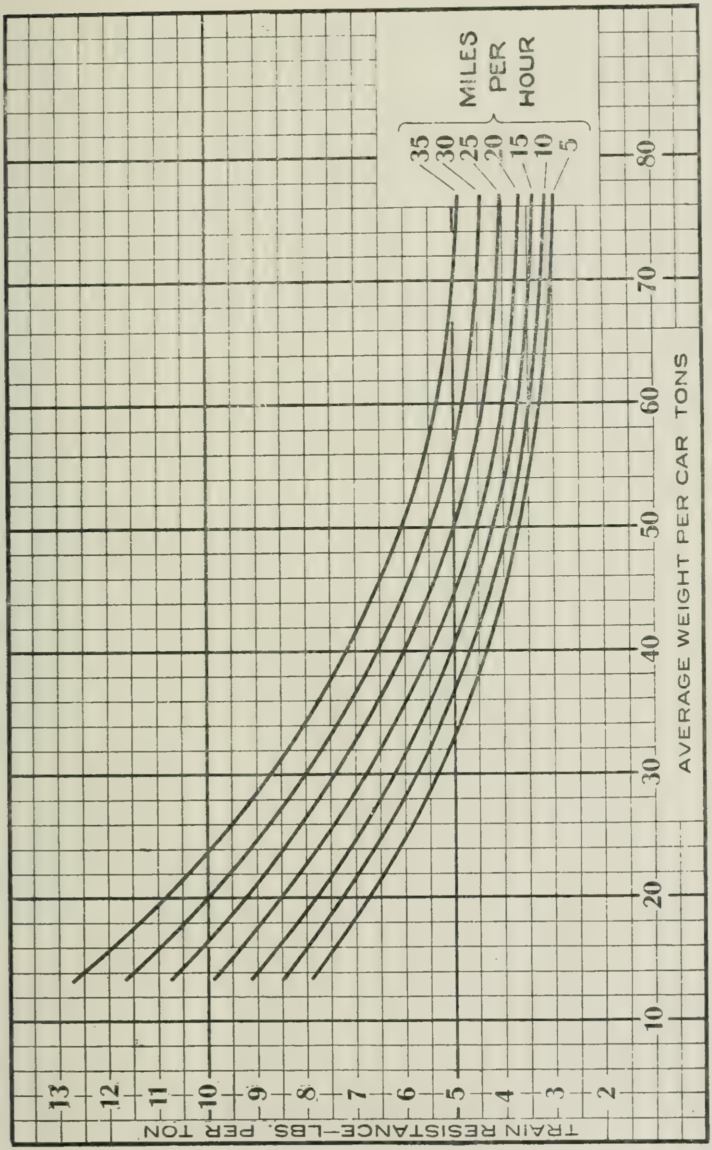

Fig. 10 The Relation Between Resistance and Average Car Weight, at Various Speeds

be required for this purpose each of which will apply only to a definite average car weight. Fig. 11 presents such a group of resistance-speed curves, which have been derived directly from the curves of Fig. 10. Fig. 11 therefore exhibits in different form only such information as is obtainable from Fig. 10.

The relation between the two figures may be made clear by explaining the derivation of the upper curve in Fig. 11,—the one applying to a car weight of 15 tons. In Fig. 10 the ordinate corresponding to an average car weight of 15 tons cuts the seven curves there drawn at 7 points, at which the mean resistance values are 7.62, 8.20, 8.81, 9.56, 10.37, 11.24 and 12.25 lb. per ton, corresponding to speeds of 5, 10, 15, 20, 25, 30 and 35 miles per hour, respectively. These values are the coordinates of 7 points on a resistance-speed curve applying to a car weight of 15 tons. These 7 points have been plotted in Fig. 11 and the upper curve there shown has been passed through them and extended to 40 miles per hour. The other curves of Fig. 11 were derived by a like process. In the original diagram three additional curves, corresponding to 55, 65, and 70 tons per car, were drawn. These three curves have been omitted from the figure to avoid confusion. Fig. 11 reproduces quite exactly the facts presented in Fig. 10[1]; and presents the final results of the experiments.

22. *The Results Expressed in Tabular Form.*—From each of the curves of Fig. 11 the values of resistance at various speeds have been determined and set down in Table 3. Table 3 also includes the coordinates of the resistance curves corresponding to 55, 65, and 70 tons per car, which are omitted from Fig. 11.

23. *The Results Expressed As Equations.*—The relation between resistance and speed shown by each of the curves of Fig. 11 may also be expressed in the form of an equation. Formulas 1 to 13 below are such equations, by means of which resistance may be calculated for any speed and for various car weights. In the formulas, R is the resistance expressed in pounds per ton, S is the speed expressed in miles per hour, and W is the average weight of the cars in the train expressed in tons. The formulas are purely empirical, and are simply equations of parabolas so

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[1] The points derived from Fig. 10 have been omitted from the tracing from which Fig. 11 was reproduced. All such points lie very close to the curves drawn in Fig. 11, the maximum deviation amounting to but ¾ of one per cent of the corresponding curve ordinate. In Appendix 6 there are presented tables of coordinates, by means of which Fig. 10 and 11 may be exactly reproduced.

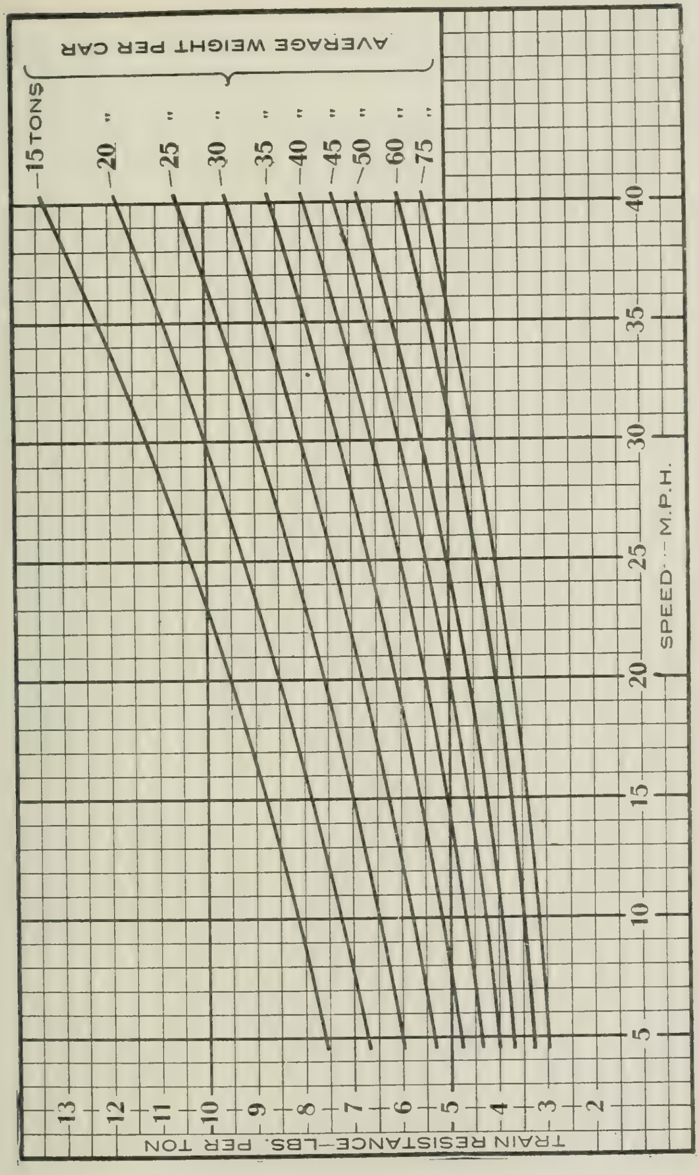

FIG. 11 THE RELATION BETWEEN RESISTANCE AND SPEED, FOR VARIOUS AVERAGE WEIGHTS PER CAR

selected as to correspond very closely with the curves of Fig. 11. The correspondence between the formulas and the curves is such that the maximum difference between any value of resistance obtained by the formulas and the corresponding value obtained from the curves of Fig. 11 is ½ of one per cent. Since these are empirical equations, their use should not be extended beyond the speed limits shown on Fig. 11.

TRAIN RESISTANCE FORMULAS.

When $W = 15$ tons; $R = 7.15 + 0.085\,S + 0.00175\,S^2$. (*1*)
When $W = 20$ tons; $R = 6.30 + 0.087\,S + 0.00126\,S^2$. (*2*)
When $W = 25$ tons; $R = 5.60 + 0.077\,S + 0.00116\,S^2$. (*3*)
When $W = 30$ tons; $R = 5.02 + 0.066\,S + 0.00116\,S^2$. (*4*)
When $W = 35$ tons; $R = 4.49 + 0.060\,S + 0.00108\,S^2$. (*5*)
When $W = 40$ tons; $R = 4.15 + 0.041\,S + 0.00134\,S^2$. (*6*)
When $W = 45$ tons; $R = 3.82 + 0.031\,S + 0.00140\,S^2$. (*7*)
When $W = 50$ tons; $R = 3.56 + 0.024\,S + 0.00140\,S^2$. (*8*)
When $W = 55$ tons; $R = 3.38 + 0.016\,S + 0.00142\,S^2$. (*9*)
When $W = 60$ tons; $R = 3.19 + 0.016\,S + 0.00132\,S^2$. (*10*)
When $W = 65$ tons; $R = 3.06 + 0.014\,S + 0.00130\,S^2$. (*11*)
When $W = 70$ tons; $R = 2.92 + 0.021\,S + 0.00111\,S^2$. (*12*)
When $W = 75$ tons; $R = 2.87 + 0.019\,S + 0.00113\,S^2$. (*13*)

The results of the tests may also be approximately expressed by the following single empirical equation in which R is expressed in terms of both S and W.

$$R = \frac{S + 39.6 - 0.031\,W}{4.08 + 0.152\,W} \ldots\ldots\ldots\ldots (14).$$

When compared with the results of the tests as shown in Figure 11, or in Table 69 in Appendix 6, this equation results in a maximum error of 9.5 per cent. This error occurs when $S = 21$ and $W = 55$. For all other values of S and W the error resulting from the use of the equation is 9.0 per cent or less.

24. *Final Results.*—The final results of the research are presented in Fig. 11, in Table 3, and in formulas 1 to 13. It is believed that by means of the figure, or the table or the formulas, the resistance of ordinary freight trains may be fairly accurately predicted; provided the conditions surrounding their operation are similar to those which prevailed during these tests. These conditions have been fully stated and are restated in the conclusions.

It is sufficient to repeat at this point that the results apply to trains running at uniform speed, on tangent and level track of good construction, during weather when the temperature is not lower than 30° F., and when the wind velocity does not exceed about 20 miles per hour.

TABLE 3

VALUES OF RESISTANCE AT VARIOUS SPEEDS AND FOR TRAINS OF DIFFERENT AVERAGE WEIGHTS PER CAR.

The values are derived directly from the curves of Fig. 11 and represent the final results of the tests.

Speed miles per hour	Train Resistance—Pounds per ton													Speed miles per hour
	Column Headings Indicate the Average Weights Per Car													
	15 tons	**20** tons	**25** tons	**30** tons	**35** tons	**40** tons	**45** tons	**50** tons	**55** tons	**60** tons	**65** tons	**70** tons	**75** tons	
5	7.6	6.8	6.0	5.4	4.8	4.4	4.0	3.7	3.5	3.3	3.2	3.1	3.0	5
6	7.7	6.9	6.1	5.5	4.9	4.4	4.1	3.8	3.5	3.3	3.2	3.1	3.0	6
7	7.8	7.0	6.2	5.5	5.0	4.5	4.1	3.8	3.6	3.4	3.2	3.1	3.1	7
8	8.0	7.1	6.3	5.6	5.0	4.6	4.2	3.9	3.6	3.4	3.3	3.2	3.1	8
9	8.1	7.2	6.4	5.7	5.1	4.6	4.2	3.9	3.6	3.4	3.3	3.2	3.1	9
10	8.2	7.3	6.5	5.8	5.2	4.7	4.3	4.0	3.7	3.5	3.3	3.2	3.2	10
11	8.3	7.4	6.6	5.9	5.3	4.8	4.3	4.0	3.7	3.5	3.4	3.3	3.2	11
12	8.4	7.5	6.7	6.0	5.4	4.8	4.4	4.0	3.8	3.6	3.4	3.3	3.3	12
13	8.6	7.6	6.8	6.1	5.5	4.9	4.5	4.1	3.8	3.6	3.5	3.4	3.3	13
14	8.7	7.8	6.9	6.2	5.5	5.0	4.5	4.2	3.9	3.7	3.5	3.4	3.4	14
15	8.8	7.9	7.0	6.3	5.6	5.1	4.6	4.2	3.9	3.7	3.6	3.5	3.4	15
16	9.0	8.0	7.1	6.4	5.7	5.1	4.7	4.3	4.0	3.8	3.6	3.5	3.5	16
17	9.1	8.1	7.2	6.5	5.8	5.2	4.8	4.4	4.1	3.9	3.7	3.6	3.5	17
18	9.3	8.3	7.4	6.6	5.9	5.3	4.8	4.5	4.1	3.9	3.7	3.7	3.6	18
19	9.4	8.4	7.5	6.7	6.0	5.4	4.9	4.5	4.2	4.0	3.8	3.7	3.6	19
20	9.6	8.5	7.6	6.8	6.1	5.5	5.0	4.6	4.3	4.0	3.9	3.8	3.7	20
21	9.7	8.7	7.7	6.9	6.2	5.6	5.1	4.7	4.3	4.1	3.9	3.9	3.8	21
22	9.9	8.8	7.9	7.0	6.3	5.7	5.2	4.8	4.4	4.2	4.0	3.9	3.8	22
23	10.0	9.0	8.0	7.1	6.4	5.8	5.3	4.9	4.5	4.3	4.1	4.0	3.9	23
24	10.2	9.1	8.1	7.3	6.6	5.9	5.4	4,9	4.6	4.3	4.2	4.1	4.0	24
25	10.4	9.3	8.3	7.4	6.7	6.0	5.5	5.0	4.7	4.4	4.2	4.1	4.0	25
26	10.5	9.4	8.4	7.5	6.8	6.1	5.6	5.1	4.8	4.5	4.3	4.2	4.1	26
27	10.7	9.6	8.5	7.7	6.9	6.2	5.7	5.2	4.8	4.6	4.4	4.3	4.2	27
28	10.9	9.7	8.7	7.8	7.0	6.3	5.8	5.3	4.9	4.7	4.5	4.4	4.3	28
29	11.1	9.9	8.8	7.9	7.1	6.5	5.9	5.4	5,0	4.8	4.6	4.5	4.4	29
30	11.3	10.0	9.0	8.0	7.3	6.6	6.0	5.5	5.1	4.9	4.7	4.5	4.5	30
31	11.4	10.2	9.1	8.2	7.4	6.7	6.1	5.6	5.2	5.0	4.8	4.6	4.5	31
32	11.6	10.4	9.3	8.3	7.5	6.8	6.2	5.8	5.3	5.0	4.9	4.7	4.6	32
33	11.8	10.5	9.4	8.5	7.6	7.0	6.3	5.9	5.4	5.2	5.0	4.8	4.7	33
34	12.0	10.7	9.6	8.6	7.8	7.1	6.5	6.0	5.5	5.3	5.1	4.9	4.8	34
35	12.3	10.9	9.7	8.8	7.9	7.2	6.6	6.1	5.7	5.4	5.2	5.0	4.9	35
36	12.5	11.1	9.9	8.9	8.0	7.4	6.7	6.2	5.8	5.5	5.3	5.1	5.0	36
37	12.7	11.2	10.0	9.0	8.2	7.5	6.9	6.4	5.9	5.6	5.4	5.2	5.1	37
38	12.9	11.4	10.2	9.2	8.3	7.6	7.0	6.5	6.0	5.7	5.5	5.3	5.2	38
39	13.1	11.6	10.4	9.4	8.5	7,8	7.1	6.6	6.2	5.8	5.6	5.4	5.3	39
40	13.4	11.8	10.6	9.5	8.6	7.9	7.3	6.8	6.3	6.0	5.7	5.6	5.5	40

VII. DISCUSSION OF THE RESULTS

25. *Variation in Resistance of Different Trains.*—Reference has been made to the variations among the points of Fig. 3 to 9. In

each figure about one half of the points lie above the curve there drawn, and their resistance values vary from those of the curve by different amounts. It should be borne in mind that, in these figures, each point represents the average resistance which prevailed throughout a particular test, and differences among the points represent, therefore, differences in the mean resistance of the different trains.

Among those trains which are regarded as normal there are two or three whose resistance at some speed varies from the mean, as expressed in the curves, by as much as 23 per cent. The great majority, however, vary from this mean by about 10 per cent or less. In Fig. 4, for example, there are 19 points which lie above the curve, among which the maximum deviation from the mean is 23 per cent, while the average of the deviations for all 19 points is 8 per cent. The following table presents similar average deviations above and below the mean for each of Fig. 3 to 9.

AVERAGE DEVIATION OF ALL POINTS IN FIG. 3 TO 9, FROM THE MEAN AS SHOWN BY THE CURVES THERE DRAWN.—EXPRESSED AS PERCENTAGES OF THE CURVE ORDINATES.

	Fig. 3 5 m. p. h.	Fig. 4 10 m. p. h.	Fig. 5 15 m. p. h.	Fig. 6 20 m. p. h.	Fig. 7 25 m. p. h.	Fig. 8 30 m. p. h.	Fig. 9 35 m. p. h.
Points above the curve	11	8	8	11	13	8	7
Points below the curve	13	10	9	8	9	9	9

The data present no satisfactory general explanation for these differences in the resistance of different trains of like average weight per car. They may be due to difference in external conditions or to difference in train condition and make-up. Whatever may be the explanation for these differences it is significant that about one-half of the trains experimented upon developed a resistance about 9 per cent in excess of the mean resistance which would be predicted by the use of Fig. 3 to 9 and Fig. 10 and 11. Obviously a similar excess may be expected with any train, and it is suggested therefore that, in determining the resistance of trains on *level tangent track* for the purpose of rating locomotives under operating conditions which demand conservative ratings, 9 per cent be added to the resistance values obtained from the curves, tables, and equations presented. Such considerations are of little practical importance in rating locomotives for speeds above 15 miles per hour. In such cases an excess in resistance over that expected can result in nothing more serious than failure to realize the expected train speed.

It should be understood that this 9 per cent allowance is intended to cover probable variations in the resistance of different trains under normal operating conditions. It in no way takes the place of that additional reserve which must be allowed to cover unusual variations in resistance due to low temperatures or high winds, or of that reserve in tractive effort of the locomotive which is necessitated by operating conditions which reduce the efficiency of the locomotive itself.

26. *Tests Which Present Abnormal Resistance Values.*—There are four points in Fig. 3 to 9 whose deviation from the curves is so great as to demand special examination. These are the points corresponding to tests S–1034, S–1074, S–1080, and S–1031 (points 34, 74, 80, and 31). These tests show a persistent and great variation from the mean at various speeds. The trains of tests 1034, 1074, and 1080 were alike in having average car weights less than 23 tons and in containing a large proportion of empty gondolas, 99, 98, and 84 per cent, respectively. Any explanation based on the train composition is however nullified by the fact that the trains of tests No. 1016, 1043, and 1063, which show close correspondence with the curves, had similar average car weights and contained almost equally large proportions of empty gondolas. Weather and wind conditions likewise offer no explanation of the divergences presented by these three tests. Explanations are rendered more difficult by the fact that, while the trains of tests 1034 and 1074 show unusually high resistance, the resistance in test 1080 is exceptionally low. The abnormalities presented by these three trains have therefore been accepted as unexplained by the data at hand.

The resistance of the trains of the fourth test mentioned above (S–1031) is low at all speeds. This train had an average car weight of 20.7 tons, contained 94 per cent of box cars, and was only 1425 ft. long. Other test trains of similar average car weight differ from this in having generally less than 60 per cent of box cars and in being all 2400 ft. or more in length. Taking into consideration all the data, neither fact seems, however, to offer an adequate explanation of the variations exhibited by this train.

27. *Car Weight as a Basis of Expression.*—Objection may be made to the form of expression adopted in Fig. 3 to 9 and 10, in which the resistance is expressed solely in terms of average car weight, to the apparent neglect of the influence of those elements of resistance, such as air resistance, which are independent of weight and which probably vary only with the number of cars in the train. The neglect is only apparent, however, for the process by which Fig. 10 was derived involves, although indirectly, the recognition of the influence of the number of cars. It is quite likely that, if Fig. 10 were applied to determine the total resistance of a single car, the result would be in error.

Whatever objection may be urged against the form of expression adopted, it remains true that Fig. 10 rests upon experimental results obtained with trains of usual length and that in practice one is not likely to encounter trains which present in this respect any extreme variation from the test data. The form of expression will not lead to error unless misapplied and it was chosen because it permits the results to be conveniently used in establishing tonnage ratings.

It might likewise have been more rational to express the resistance in terms of load per axle instead of load per car, since the latter can operate to cause variations in resistance only in so far as it affects the former. Since, however, all American freight cars have four axles, the expression in either form would be identical. Convenience in application warrants the choice made in this respect also.

28. *Effect of Variety in Car Weight upon Total Train Resistance.*—In Fig. 10 those portions of the curves which apply to average car weights below 20 tons were derived from trains which were quite homogeneous in their make-up as regards weight per car. These trains were necessarily composed almost exclusively of empty cars, since an average car weight of 20 tons or less cannot be obtained with cars of current design unless they are empty or nearly so, and being empty they will be uniform in weight. Similarly for average car weights above 55 or 60 tons, the test trains were necessarily uniform in make-up. For trains of average car weights below 20 and above 60 tons, the curves of Fig. 10 are ac-

cepted, therefore, as valid and applicable to any train to be met with in practice.

In Fig. 10, those portions of the curves corresponding to car weights of from 20 to 60 tons were, on the other hand, derived from trains which presented considerable diversity in make-up as regards weight per car. Some of these trains were composed almost entirely of loaded cars, others contained large proportions of both empty and loaded cars. In presenting the results in the form adopted in Fig. 10 (and Fig. 11) the assumption is that the curves there drawn will be used throughout their entire range of average car weight to determine the total resistance of both homogenous and mixed trains, and that, when so applied, they will lead to no material error. In view of the facts just stated it is pertinent to inquire whether this assumption is justifiable.

Assume two trains of equal tonnage, and of the same average weight per car. Assume further that one is composed of cars uniform in weight, and that the other is composed of cars of different individual weights. Now if such trains are to have equal total resistance, it can be shown that the variation in the resistance *per car* of the individual cars must be directly proportional to their weight. This implies that the curve showing the relation between *total car resistance* and car weight at a given speed must be a straight line, if homogeneous and mixed trains are to have equal total resistances at this speed. From Fig. 10 there have been derived curves showing this relation between car resistance and car weight. These curves (not shown in the report) correspond quite closely, but not exactly, with straight lines; and the correspondence is especially close for those portions of the curves which apply to car weights between 20 and 60 tons. From these facts we may conclude that the curves of Fig. 10 are not quite, but are nearly equally applicable to mixed and homogeneous trains, and that, if the curves are applied to both kinds of trains, we may expect a slight error in the resulting total train resistance. The amount of such error is indicated by the following examination of a specific case.

Assume two trains, A and B, the first homogeneous, the second mixed, as regards car weight. Train A is composed of 60 cars, each weighing 45 tons, and its total weight is 2700 tons. Train B is composed of 30 cars of 70 tons each, and 30 cars of 20 tons each; its total weight is 2700 tons and its average car weight is 45 tons. Train B presents about as great a diversity in car weight as may be encountered in current practice. Both trains have equal tonnage and the same average weight per car. Assume that the total resistance of these two trains at a speed of 5 miles per hour is to be determined. By the procedure, which it is intended shall usually be followed in using Fig. 10, the resistance for an average car weight of 45 tons, at 5 miles per hour, is found to be 4.0 lb. per ton; and the total resistance of either train A or train B is 2700 x 4.0 =10 800 lb.

Train B, however, may be considered as made up of two shorter homogeneous trains of average car weights of 20 and 70 tons respectively and the resistance of each may be determined from those portions of the curves of Fig. 10, about whose validity no question is raised. From Fig. 10, the resistance at 5 miles per hour for a car weight of 20 tons is found to be 6.8 lb. per ton and for a car weight of 70 tons, 3.1 lb. per ton. By the use, therefore, of these portions of the curves of Fig. 10, the total resistance of train B is found to be 30 x 20 x 6.8 + 30 x 70 x 3.1 = 10 590 lb., which differs from the resistance previously found by 2 per cent. If a similar analysis be made for a speed of 40 miles per hour, the corresponding difference is found to be 4 per cent. If these differences be accepted as a measure of the maximum error likely to result from the indiscriminate application of the curves of Fig. 10 to mixed and homogeneous trains, we may conclude that for purposes of rating locomotives the results of the tests as expressed in Fig. 10 and 11 and Table 3 may be so applied without material error.

29. *The Influence of Speed on Resistance.*—Within the last two years the opinion has been expressed in some quarters that train resistance between speeds of 5 and 35 miles per hour is constant. It is proper to point out that there is nothing in the data here presented to support such a conclusion.

30. *The Influence of Wind Velocity on Resistance.*—The wind velocities prevailing during the tests were generally less than 20 miles per hour. The data do not permit the influence of such winds to be differentiated from the other elements affecting resistance; but they do warrant the conclusion that this influence is small. In the introduction, train resistance was defined as the

resistance in still air, whereas throughout the report the term is used to apply to the test results from which the influence of wind has not been eliminated. This inconsistency has been deliberately incurred to avoid unwieldy expression and is partially justified by the facts just stated.

31. *Comparison with Other Experiments.*—There is no point in comparing the results of these tests with formulas in which the influence of car weight is given no consideration, nor with those which are not derived from tests with American cars of recent design. The results obtained on the Chicago, Burlington and Quincy Railroad and on the Pennsylvania Railroad, and recently published by Mr. F. J. Cole,[1] take into consideration the influence of car weight and they apply to cars of recent design. They are therefore selected for comparison.

The results obtained on the Chicago, Burlington and Quincy road (curve No. 1, for temperatures above 30° F. and no wind) apply to a speed of 20 miles per hour. Compared with the curve for 20 miles per hour in Fig. 10, they show resistance values which are from 35 to 60 per cent lower than the corresponding results of these tests. The Pennsylvania Railroad results are claimed to be equally applicable at all speeds between 5 and 30 miles. When plotted on Fig. 10 of this report they show very close correspondence with the curve there drawn for 10 miles per hour, for car weights from 25 to 70 tons; while for car weights below 25 tons they indicate resistance values as much as 20 per cent in excess of the results obtained during these tests.

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[1] Railway Age Gazette, August 27 to October 1, 1909.

APPENDIX 1

APPENDIX 1

RAILWAY TEST CAR NO. 17

The dynamometer car by means of which these tests were made was built in 1900. Under the arrangements perfected at that time, the car was built and has since been maintained by the Illinois Central Railroad, while the University has supplied all apparatus, and has manned and operated the car. Both the car body and the apparatus were remodeled in 1907[1].

The car body was especially designed for its purpose. It is 40 ft. long over the end sills, and 8 ft. 4 in. wide inside. The central sills and the platforms are of steel, while the remainder of the construction is of wood. The general design of the car is shown in Fig. 12, and an interior view is shown in Fig. 13. The working space occupies about two thirds of the length of the car, and in it are placed the recording apparatus, the auxiliary instruments, the storage batteries, work-bench, etc.

During the tests, the test car apparatus made continuous autographic records of drawbar pull, speed, time, mile post positions, airbrake cylinder pressure, wind velocity with respect to the car, and wind direction with respect to the longitudinal axis of the car. These records are made upon a chart 36 in. wide, drawn across the table of the recording apparatus. This chart was driven by gearing from the axle of the central truck below the car, so that its travel was proportional to the travel of the car itself. In all tests a car travel of one mile produced a paper travel of 13.2 in. A view of the recording apparatus is shown in Fig. 14.

Fig. 15 is reproduced from a tracing of a portion of the chart made during test S-1057 of this series. The only lines there shown which do not appear on the original record are the profile and the transverse lines which mark the limits of one of the sections selected for calculation. These lines and some of the explanatory lettering have been added to the tracing, in order to make clearer the significance of the various records.

The total pull which comes upon the measuring drawbar of the car is transmitted to oil contained in the receiving cylinder, the design of which is shown in Fig. 16. This cylinder is hung

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[1] A more detailed description of the present equipment is contained in an article by F. W. Marquis, in the Railway Age Gazette February 19, 1909.

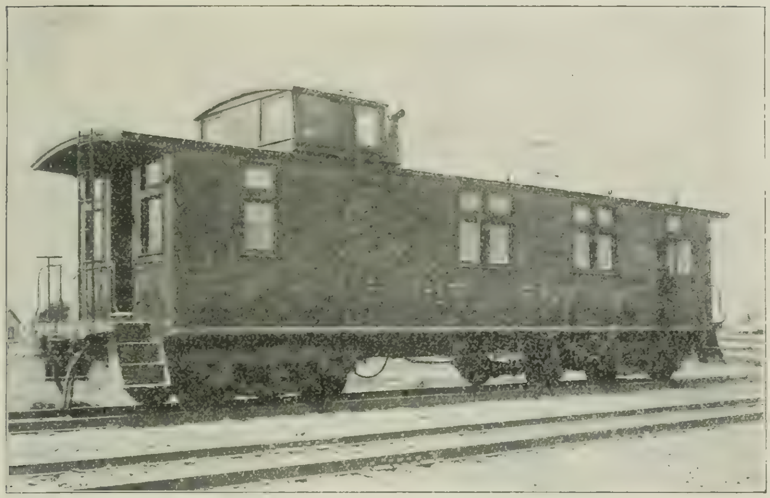

FIG. 12 RAILWAY TEST CAR NO. 17

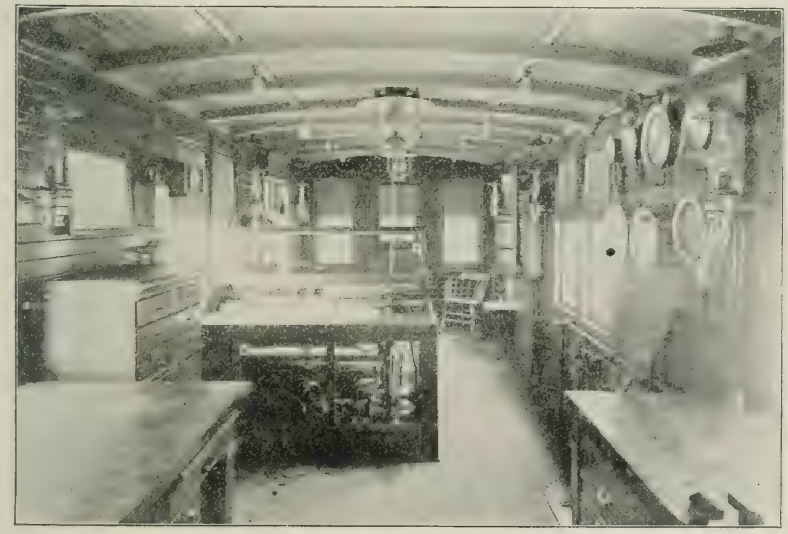

FIG. 13 INTERIOR OF TEST CAR NO. 17

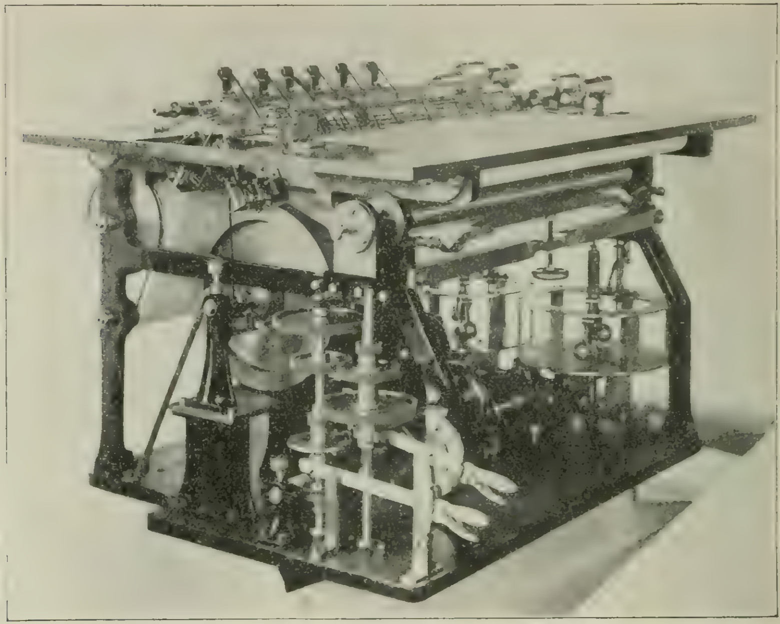

FIG. 14 THE RECORDING APPARATUS

from the center sills, immediately behind the drawbar yoke. Its inside diameter is 10 in., and its piston is $7\frac{1}{2}$ in. long. Both cylinder and piston are carefully ground to an exact fit and no piston packing is used. The pull is transmitted from the drawbar yoke to the piston through a roller-borne yoke; and the whole device is practically frictionless. Such leakage of oil as takes place proceeds so slowly as to prove no inconvenience, even when operating under maximum pull. The cylinder may be refilled with oil by means of a pump within the car, and this is done while the car is in operation and without impairing the accuracy of the record. The pressure of the oil in this receiving cylinder is transmitted to the cylinder of an indicator located upon the table within the car. This indicator is identical, in its design, with one of the modern types of steam engine indicators, although it is larger and heavier throughout. During its ten years of service this type of dynamometer has demonstrated its reliability and accuracy.

Two speed records are shown on the chart, and both are used. The one is obtained from a speed recorder which resembles in design a "fly-ball" engine governor. This instrument is used in measuring speeds above 15 miles per hour. The second record is obtained from a chain-driven Boyer speed recorder, geared to run at a speed about three times as great as is usual with these instruments. This record is used for speeds up to 35 miles per hour. Within their respective ranges, both instruments produce accurate speed curves.

The air-brake cylinder of the test car is connected to the cylinder of an ordinary steam engine indicator, which is mounted upon the table and which draws a curve of air-brake cylinder pressure.

The velocity of the wind with respect to the car is obtained by means of a Robinson cup-anemometer of the standard United States Weather Bureau type, which is so mounted that the cups revolve 32 in. above the car roof. This instrument controls an electric circuit, which operates an electro-magnet connected to the recording pen. By means of this magnet offsets are made in the line drawn by the pen. During the time which elapses between two successive offsets, the travel of the air past the cups amounts to 0.2 of a mile.

The direction of the wind with respect to the longitudinal axis of the car is derived from a wind vane mounted 3 ft. above the car roof. The spindle of the vane extends downward to a point above the recording apparatus and terminates there in a crank, parallel to the vane. This crank is connected to the recording pen through a rod with a yoke end. The ordinate of the curve drawn by this pen is proportional to the sine of the angle made by the vane with the car axis. The offsets in the datum line for this curve, which appear in Fig. 15, indicate that the vane, at the moment, was pointed toward the front end of the car. While the vane points toward the rear end no offsets are made in the datum line.

Fig. 15 shows a record of "area under the curve of pull" which is made by means of a recording planimeter mounted on the table. This record is inaccurate and was not used in these calculations.

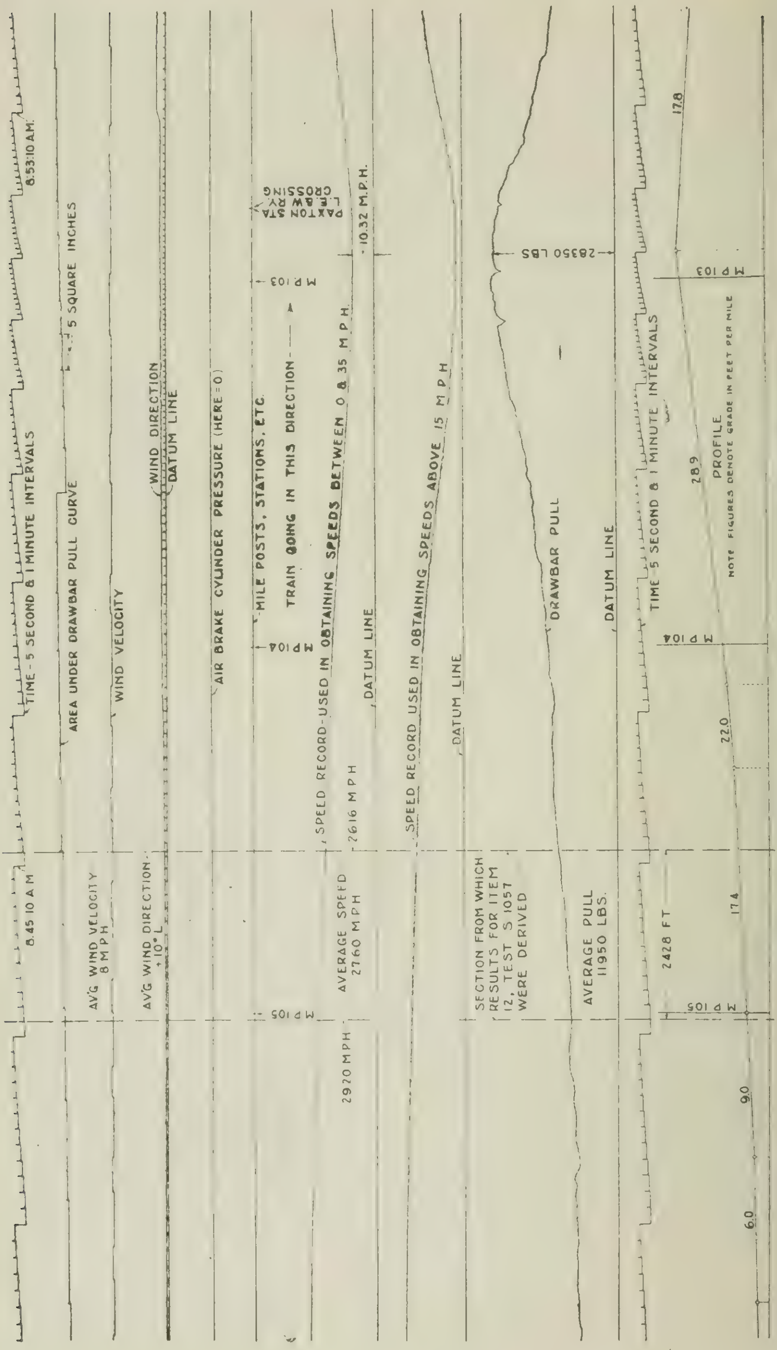

FIG. 15 A PORTION OF THE CHART FROM TEST S-1057

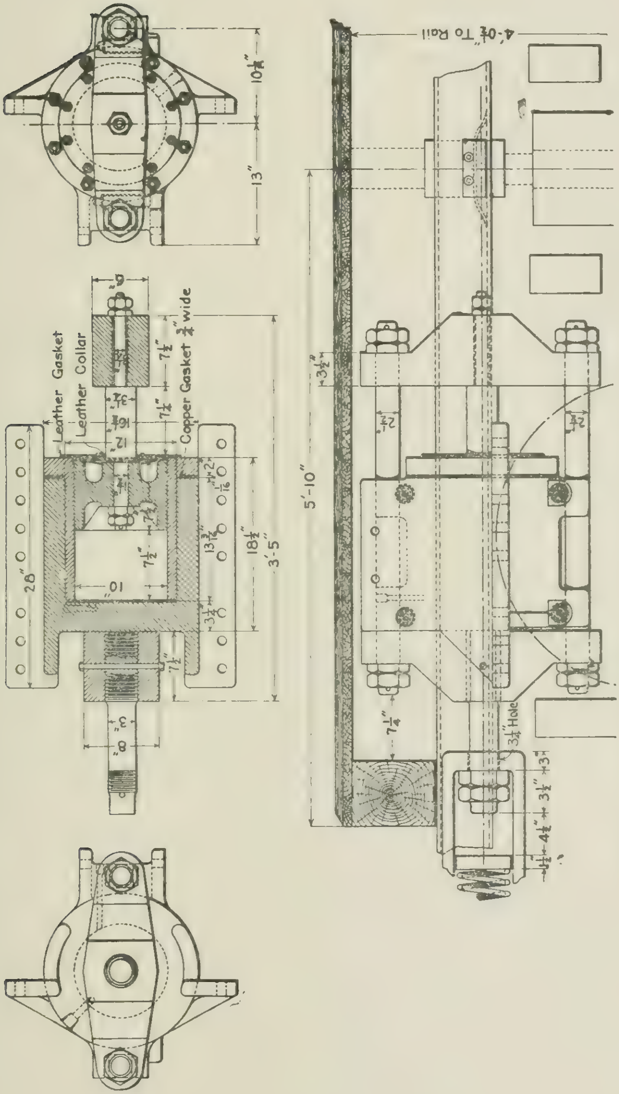

FIG. 16 THE RECEIVING CYLINDER OF THE DYNAMOMETER

APPENDIX 2

APPENDIX 2

THE TONNAGE RECORDS OF THE TRAINS

Tables 4 to 35 present the records of make-up and tonnage of the trains. The car numbers are arranged in the tables in the order in which the cars were placed in the train, beginning at the head end.

With the few exceptions cited in Part I, the weights given in the last column of the tables were obtained by weighing the train on the track scales. In all tests the dynamometer car was coupled immediately behind the locomotive tender. In the tonnage records for those tests in which the test car ran with its measuring drawbar pointed toward the rear of the train, the test car weight is excluded, since in such cases its own resistance is not included in the pull recorded on the chart.

TABLE 4 Tonnage Record

Test No. S-1013

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test Car	E			58 000		58 000
Gondola	L	82 386	I. C.	28 700	60 000	92 300
Refrigerator	E	6 641	N. C. L.		60 000	36 400
Box	L	48 887	I. C.	39 100	80 000	96 200
"	"	36 476	"	37 000	80 000	92 000
"	"	92 329	N. C. & St. L.	33 300	60 000	95 000
"	"	9 842	N. C. & St. L.	33 400	60 000	94 000
"	"	37 668	I. C.	34 600	80 000	107 000
"	"	14 301	"	29 200	60 000	72 700
Refrigerator	E	726	C. B. T.			38 200
Box	L	38 254	I. C.	34 000	80 000	58 700
Gondola	"	85 604	"	31 500	80 000	105 100
Box	"	39 840	"	38 900	80 000	82 400
"	"	9 337	L. & N.	34 500	65 000	69 300
"	"	94 116	"	35 400	65 000	64 700
"	"	3 135	"	34 000	65 000	89 600
Refrigerator	E	5 260	A. R. L.	36 500	50 000	38 100
Box	L	39 404	I. C.	38 300	60 000	122 000
Gondola	E	16 778	Erie	42 800	100 000	42 600
Box	L	38 711	I. C.	37 600	80 000	86 500
"	"	5 078	N. C. & St. L.	38 300	60 000	76 000
"	"	3 954	L. & N.	33 100	65 000	94 000
"	"	133 684	S. O.	33 200	60 000	68 000
Gondola	"	3 193	I. S.	40 200	100 000	147 800
Tank	"	704	B. T. R.			78 500
"	"	540	D. R. & U.			80 000
"	"	293	A. C. O.			88 100
Gondola	"	82 968	I. C.	28 400	60 000	83 700
Box	"	34 623	"	37 100	60 000	68 100
"	"	19 773	"	28 300	60 000	62 600
"	"	47 730	"	30 600	80 000	108 700
"	"	130 091	"	42 300	80 000	88 100
"	"	14 834	"	31 600	60 000	74 000
Refrigerator	"	5 223	M. R. T.			50 600
Box	"	48 273	I. C.	39 700	80 000	99 600
"	"	36 741	"	34 500	80 000	119 200
"	"	36 076	"	35 700	80 000	122 000
"	"	49 417	"	35 200	80 000	90 000
"	"	34 147	"	37 000	80 000	92 300
"	"	136 690	S. O.	34 300	60 000	87 800
"	"	32 645	"	31 800	60 000	36 600
"	"	17 853	I. C.	29 900	60 000	63 900
"	"	45 691	"	39 400	80 000	100 000
"	"	38 217	"	34 000	80 000	74 300
Gondola	"	93 582	"	30 400	80 000	115 600
Box	"	47 588	"	41 600	80 000	89 300
"	"	140 760	"	42 900	100 000	76 000
"	"	45 432	"	36 300	80 000	123 300
"	"	12 104	"	28 800	60 000	64 300
"	"	22 796	"	37 500	80 000	113 600
"	L	48 388	"	39 700	80 000	63 500
"	E	22 742	L. S. & M. S.	29 300	60 000	31 000
"	L	36 825	I. C.	33 900	80 000	72 000
Gondola	"	79 267	"	24 800	50 000	27 000
Box	"	12 784	"	28 300	60 000	63 000
Gondola	"	81 750	"	26 700	60 000	65 500
Refrigerator	E	275	B. T.	28 000	60 000	32 000
Box	"	11 972	W. C.	29 900	60 000	29 300
"	L	12 658	I. C.	37 400	80 000	63 000
"	E	45 051	"	36 000	60 000	67 000
"	L	20 670	"	28 500	60 000	84 000
"	"	17 783	"	29 800	60 000	63 000
"	"	141 980	"	43 700	100 000	74 000
"	"	15 026	"	30 000	60 000	70 000
Gondola	"	6 232	S. I.	28 500	60 000	80 000
Refrigerator	"	6 003	A. R. L.	34 800	50 000	45 100
Caboose	E	98 018	I. C.	34 000		34 000

TABLE 5 Tonnage Record

Test No. S-1015

Kind of Car	Loaded or Empty	Car No.	Ca Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Gondola	L	89 299	I. C.	32 000	80 000	82 000
"	"	91 712	"	29 400	80 000	80 000
Box	"	130 646	"	42 300	80 000	92 000
Tank		500	Champ'n stock	32 100	60 000	96 000
Box	"	24 678	I. C.	36 000	80 000	67 000
"	"	23 251	"	25 200	80 000	92 300
"	"	140 501	"	42 700	100 000	81 500
"	"	141 254	"	43 500	100 000	96 300
Tank		185	A. P. L.			78 000
Box	"	8 457	I. C.	30 100	50 000	93 100
"	"	26 732	"	36 100	80 000	114 400
"	"	13 635	"	28 900	60 000	84 600
"	"	11 069	"	30 200	60 000	96 600
"	"	23 530	"	36 100	80 000	98 000
"	"	12 235	"	28 800	60 000	90 900
"	"	17 652	"	28 900	60 000	83 300
"	"	37 500	"	34 100	80 000	100 000
"	"	39 126	"	36 700	80 000	95 500
"	"	17 644	"	30 000	60 000	75 800
"	"	12 774	"	30 400	60 000	81 400
"	"	33 666	"	36 100	80 000	84 300
"	"	6 985	"	27 700	50 000	80 600
Gondola	"	86 493	"	30 800	80 000	102 000
Box	"	83 722	S. Pa.	33 900	80 000	123 000
"	"	5 000	A. R. L.	34 800	50 000	38 500
"	"	11 598	N. C. & St. L.	33 200	60 000	99 100
"	"	6 902	N. C. & St. L.	29 900	60 000	66 100
"	"	35 113	S. L. & S. F.	35 100	60 000	80 400
"	"	29 220	I. C.	38 100	60 000	53 500
Gondola	"	91 289	"	29 000	80 000	70 600
Flat	"	8 146	I. S.	33 200	100 000	115 500
Box	"	39 343	I. C.	36 600	80 000	95 000
"	"	141 804	"	43 500	100 000	84 500
"	"	141 686	"	43 500	100 000	103 500
"	E	25 376	M.St.P.&S.SM	33 500	60 000	33 600
"	L	140 755	I. C.	42 900	100 000	48 500
"	"	56 092	U. P.	25 800	50 000	72 800
"	"	15 503	I. C.	28 800	60 000	70 000
"	E	13 330	C. G. W.	30 000	60 000	29 700
Flat	L	10 638	V.	24 500	60 000	33 800
"	"	10 521	V.	21 200	60 000	31 700
Box	"	45 514	I. C.	39 100	80 000	78 600
"	"	142 175	"	42 800	100 000	81 300
"	"	22 064	"	37 800	80 000	76 000
"	"	46 450	"	37 600	80 000	78 000
"	"	58 576	"	33 800	80 000	85 000
Refrigerator	"	33 476	C. & N. W.	32 200	50 000	56 000
Box	"	12 530	I. C.	30 500	60 000	59 600
Tank	"	990	A. P. L.			82 300
Box	"	46 660	I. C.	38 000	80 000	67 400
"	"	49 154	"	35 200	80 000	70 300
Refrigerator	"	6 502	U. R. T. C.	30 800	100 000	47 700
Flat	"	65 226	I. C.	23 900	60 000	71 200
Box	"	140 108	"	42 900	100 000	125 600
Refrigerator	"	4 531	N. C. L.		50 000	41 600
Tank	"	150	A. T. L.			80 100
"	"	153	"			78 600
"	"	1 017	"			82 000
Box	"	140 161	I. C.	42 700	100 000	73 600
Tank	"	904	A. T. L.			81 100
Box	E	82 244	C. & N. W.	32 600	80 000	32 800
Flat	L	1 549	C. H. & D.	21 400	50 000	26 000
"	"	1 799	"	21 700	40 000	38 400
"	"	67 930	I. C.	26 800	80 000	35 700
"	"	878	G. & S. I,			54 700
"	E	30 237	C. & H. R.	27 000	80 000	27 100
"	"	16 056	P. M.	22 600	60 000	22 400
Flat	"	8 249	N,Y.N.H. & H.	28 900	80 000	28 800
Caboose	"	98 100	I. C.			40 000

TABLE 6 TONNAGE RECORD

Test No. S-1016

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Gondola	"	93 191	I. C.	35 300	80 000	35 300
"	"	90 844	"	32 900	80 000	32 900
"	"	88 459	"	31 500	80 000	31 500
"	"	94 843	"	31 700	80 000	31 700
"	"	82 365	"	26 800	60 000	26 800
"	"	92 596	"	30 200	80 000	30 200
"	"	81 323	"	28 600	60 000	28 600
"	"	93 948	"	31 800	80 000	31 800
"	"	84 190	"	27 000	60 000	27 000
"	"	252	S. S. C.	25 500	50 000	25 500
"	"	616	E. F. D. & Co.	23 700	50 000	23 700
"	"	85 594	I. C.	31 400	80 000	31 400
"	"	84 200	"	27 400	60 000	27 400
"	"	95 241	"	30 100	80 000	30 100
"	"	3 252	I. S.	40 300	100 000	40 300
"	"	82 622	I. C.	27 800	60 000	27 800
"	"	106 404	"	40 300	100 000	40 300
"	"	93 494	"	29 600	60 000	29 600
"	"	86 663	"	31 100	80 000	31 100
"	"	96 262	"	31 800	80 000	31 800
"	"	95 707	"	30 800	80 000	30 800
"	"	83 544	"	28 200	60 000	28 200
"	"	93 960	"	31 300	80 000	31 300
"	"	87 697	"	33 500	80 000	33 500
"	"	96 062	"	31 400	80 000	31 400
"	"	76 634	"	25 700	50 000	25 700
"	"	91 067	"	30 200	80 000	30 200
"	"	91 424	"	30 600	80 000	30 600
"	"	89 402	"	32 000	80 000	32 000
"	"	115 127	"	42 600	100 000	42 600
"	"	106 777	"	40 300	100 000	40 300
"	"	104 930	"	40 600	100 000	40 600
"	"	95 782	"	31 500	80 000	31 500
"	"	104 131	"	40 600	100 000	40 600
"	"	92 338	"	30 600	80 000	30 600
"	"	81 653	"	26 400	60 000	26 400
"	"	96 137	"	31 000	80 000	31 000
"	"	88 950	"	31 800	80 000	31 800
"	"	115 043	"	43 200	100 000	43 200
"	"	80 128	"	28 900	60 000	28 900
"	"	94 357	"	30 900	80 000	30 900
"	"	96 123	"	31 200	80 000	31 200
"	"	91 024	"	31 000	80 000	31 000
"	"	84 272	"	27 500	60 000	27 500
"	"	85 516	"	29 400	80 000	29 400
"	"	86 283	"	31 600	80 000	31 600
"	"	87 090	"	30 900	80 000	30 900
"	"	83 604	"	27 300	60 000	27 300
"	"	80 933	"	27 500	60 000	27 500
"	"	83 243	"	28 000	60 000	28 000
"	"	85 624	"	30 800	80 000	30 800
"	"	75 812	"	26 000	50 000	26 000
"	"	85 649	"	30 700	80 000	30 700
"	"	88 925	"	31 900	80 000	31 900
"	"	93 575	"	31 100	80 000	31 100
"	"	104 318	"	40 800	100 000	40 800
"	"	86 327	"	30 400	80 000	30 400
"	"	94 273	"	30 100	80 000	30 100
"	"	80 921	"	28 200	60 000	28 200
"	"	82 167	"	26 900	60 000	26 900
"	"	101 116	"	38 500	100 000	38 500
"	"	86 515	"	30 400	80 000	30 400
"	"	88 352	"	31 200	80 000	31 200
"	"	104 944	"	40 200	100 000	40 200
"	"	105 533	"	40 500	100 000	40 500
"	"	262	S. S. C.	30 600	80 000	30 600
"	"	89 849	I. C.	32 000	80 000	32 000
"	"	95 296	"	30 000	80 000	30 000
"	"	93 197	"	31 400	80 000	31 400
"	"	106 428	"	40 300	100 000	40 300
Caboose	"	98 172	"	40 000		40 000

TABLE 7 TONNAGE RECORD

Test No. S-1017

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Box	L	32 302	I. C.	32 500	60 000	96 500
Gondola	"	3 363	I. S.	40 300	100 000	140 800
Box	"	9 009	I. C.	27 700	50 000	74 000
"	"	48 654	"	38 500	80 000	96 100
"	"	12 968	"	29 200	60 000	65 100
"	"	150 867	"	30 000	40 000	73 700
"	"	17 772	"	29 400	60 000	90 800
"	"	10 673	"	31 700	60 000	96 800
"	"	130 783	"	42 300	80 000	130 600
"	"	150 961	"	30 500	40 000	75 900
"	"	11 350	"	29 700	60 000	69 300
Refrigerator	"	6 638	U. R. T.	34 800	40 000	52 000
Box	"	141 330	I. C.	43 700	100 000	76 000
"	"	141 589	"	43 600	100 000	114 000
"	"	24 682	"	35 800	80 000	80 000
"	"	22 896	"	37 000	80 000	86 000
"	"	24 158	"	35 500	80 000	72 000
"	"	22 041	"	37 800	80 000	86 000
"	E	107 946	C. & N. W.	36 600	80 000	37 000
"	L	47 421	I. C.	41 500	80 000	116 000
"	"	10 485	"	29 400	60 000	92 800
"	"	130 247	"	42 400	80 000	132 000
"	"	22 942	"	36 800	80 000	123 800
"	"	22 968	"	36 600	80 000	115 700
"	"	141 969	"	43 500	100 000	119 500
"	"	32 317	"	31 100	60 000	98 400
"	"	22 318	"	38 200	80 000	56 700
"	"	11 165	"	30 300	60 000	71 800
"	"	8 390	"	31 200	60 000	77 500
"	"	142 726	"	42 800	100 000	62 000
"	"	7 698	L. & N.	28 400	60 000	60 000
"	"	1 807	"	34 200	65 000	98 000
Refrigerator	E	4 056	M. R. T.	40 400	60 000	40 000
Box	"	53 873	C. R. I. & P.	32 400	60 000	32 000
"	"	56 432	C. M. & St. P.	29 900	60 000	29 000
"	L	35 199	I. C.	36 800	80 000	105 200
"	E	10 428	W. C.	29 400	60 000	29 700
"	"	2 786	A. & W. P.	35 000	65 000	33 200
Refrigerator	"	397	W. R. T.	34 700	40 000	35 000
Gondola	"	1 025	C. & I. W.	32 200	100 000	32 000
Box	L	49 236	I. C.	34 800	80 000	103 000
"	"	14 943	"	30 800	60 000	84 600
"	"	17 142	"	30 500	60 000	84 000
"	"	22 404	"	27 900	80 000	109 000
"	"	150 265	"	29 300	40 000	65 000
"	"	5 298	Ga.	31 800	60 000	73 100
"	"	14 010	I. C.	32 200	60 000	68 900
"	"	36 980	"	31 300	80 000	81 000
"	"	48 699	"	39 300	80 000	59 300
"	"	48 721	"	39 200	80 000	77 500
"	"	21 715	"	36 200	80 000	81 500
"	"	1 292	I. L. & M.	29 200	60 000	113 000
"	"	142 255	I. C.	42 900	100 000	97 500
"	"	45 525	"	39 300	80 000	75 700
Refrigerator	E	9 056	C. R. D.	34 600		34 600
Box	L	48 739	I. C.	39 100	80 000	74 100
"	"	45 762	"	40 300	80 000	78 700
"	E	36 636	"	34 100	80 000	35 300
"	L	22 995	"	35 100	80 000	94 300
Gondola	"	106 302	"	40 300	100 000	90 500
Box	E	72 314	C. M. & St. P.	30 400	60 000	29 000
"	L	19 840	I. C.	29 300	60 000	64 300
"	"	17 625	"	29 300	60 000	58 000
"	E	64 599	N. & W.	39 500	80 000	38 800
"	L	45 386	I. C.	38 700	80 000	79 800
Caboose	E	98 023	"			40 000

TABLE 8 Tonnage Record

Test No. S-1018

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Box	L	28 594	A. T. & S. F.	36 700	70 000	113 600
..	..	73 246	C. & N. W.	29 800	80 000	92 600
..	E	49 016	I. C.	39 300	60 000	44 200
..	L	16 179	..	29 700	80 000	38 400
Gondola	..	104 113	..	40 800	100 000	131 400
Box	E	46 485	..	37 800	80 000	43 400
..	L	24 331	S. A. L.	28 900	60 000	39 200
..	E	5 372	L. R. & M.	34 600	60 000	34 400
..	..	251	O. G. & N. E.	38 700	80 000	38 800
..	..	19 944	South	31 900	60 000	33 600
Gondola	..	180 614	..	40 100	100 000	37 200
Box	..	56 649	L. & N.	41 100	50 000	42 800
..	L	45 413	Big 4.	38 100	80 000	82 200
..	..	49 161	T. C.	35 800	80 000	59 400
..	E	68 250	C. & N. W.	30 000	60 000	39 200
..	L	39 546	..	33 500	60 000	51 000
Locomotive		423	I. C.			145 200
Flat	L	66 644	..	29 000	80 000	65 800
Tank	..	6 059	S. I.		8 000 Gal.	35 200
..	E	6 052	..		8 000 Gal.	41 600
..	..	6 239	..		8 000 Gal.	39 000
..	..	6 233	..		8 000 Gal.	39 400
..	..	6 054	..		8 000 Gal.	38 400
..	..	6 190	..		8 000 Gal	39 800
..	..	600	I. T. Co.	30 000	80 000	39 200
Box	..	130 857	I. C.	41 000	80 000	80 800
Tank	L	680	S. C. O. Co.	48 100	12 500 Gal	49 200
Gondola	..	3 175	I. S.	40 400	100 000	148 000
..	E	273	S. C. Co.	30 700	80 000	35 800
Locomotive		732	I. C.			223 600
Box	E	30 105	M. L. & T.	33 100	80 000	33 400
..	..	11 571	A. G. S.	34 700	60 000	34 400
..	..	2 004	D. & W.	36 900	60 000	36 200
..	..	14 533	L. & N.	33 300	65 000	34 600
..	L	558 937	Penn.	45 400	100 000	71 400
..	..	84 494	P. R. R.	30 800	60 000	55 600
..	E	9 230	N. C. & St. L.	33 300	60 000	34 000
..	L	9 264	..	30 200	60 000	31 600
..	E	6 316	..	29 100	60 000	29 800
..	..	135 068	South	33 500	60 000	33 500
..	..	13 161	..	33 800	60 000	33 800
..	..	13 761	St. L. & S. F.	34 000	60 000	34 000
..	..	32 482	South	35 600	60 000	34 000
Flat	..	1 276	G. S. I.	28 600	80 000	27 000
..	..	803	M. C.	28 500	80 000	28 500
..	..	621	..	28 500	80 000	28 500
..	..	413	G. S. F.	27 200	60 000	27 800
..	..	553	..	27 200	60 000	27 600
..	..	799	..	27 500	80 000	27 500
Caboose	..		I. C.			40 000

TABLE 9 Tonnage Record

Test No. S-1019

Box	E	46 712	I. C.	38 100	80 000	38 100
..	..	38 898	..	36 700	80 000	38 600
..	..	14 965	"	30 100	60 000	30 400
..	..	35 160	"	36 900	80 000	36 900
Flat	L	500	A. T. L. Co.	41 720	60 000	103 000
Box	..	25 173	I. C.	37 100	80 000	70 000
..	..	19 287	S. A. L.	33 300	80 000	62 000
..	..	11 539	N. C. & St. L	33 800	60 000	4 300
..	..	997	P. M	34 400	50 000	50 100
..	..	1 853	D & M.	33 100	60 000	71 100
..	..	3 768	N. C. & St. L	37 100	60 000	62 600
..	"	57 378	C. M. & St. P	29 900	80 000	70 000
..	..	33 580	I. C.	36 000	80 000	74 000
..	E	55 968	L. & N.	41 400	55 000	42 000
..	..	46 836	I. C.	38 100	80 000	36 500
..	L	16 200	..	30 000	50 000	30 000

TABLE 9 TONNAGE RECORD—(*Continued*)

Kind of Car	Loaded or Empty	Car No.	Car Intitial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Box	E	12 296	I. C.	29 400	60 000	29 000
"	"	12 302	"	29 700	60 000	30 000
"	"	37 189	"	34 500	80 000	35 000
"	"	24 525	"	36 400	80 000	36 400
"	"	37 157	"	33 600	80 000	34 500
Gondola	"	88 956	"	31 900	80 000	32 000
"	"	90 907	"	30 900	80 000	32 000
"	"	81 808	"	28 800	60 000	28 000
"	"	96 187	"	30 500	80 000	32 100
"	"	87 235	"	31 400	80 000	31 400
"	"	86 649	"	30 900	80 000	30 800
Box	"	30 249	T. R. E.	38 700	50 000	38 700
Refrigerator	"	19 529	C. F. X.	34 400	50 000	37 200
Tank	L	6 278	C. T. L.	47 000		95 200
Box	"	45 246	I. C.	37 400	80 000	37 200
"	"	142 342	"	42 700	100 000	42 700
"	E	141 780	"	43 600	100 000	43 100
"	L	7 613	"	27 100	50 000	27 100
Gondola	E	105 880	"	40 399	100 000	40 400
"	"	86 524	"	31 200	80 000	31 400
"	"	104 438	"	40 700	100 000	40 800
"	"	106 223	"	40 400	100 000	41 000
"	"	94 144	"	31 000	80 000	32 000
"	"	93 670	"	30 000	80 000	30 400
"	"	5 470	"	23 200	50 000	23 100
"	"	94 433	"	30 900	80 000	30 600
"	"	87 576	"	31 500	80 000	32 100
"	"	81 635	"	27 700	60 000	26 900
"	"	87 931	"	31 900	80 000	31 800
"	"	86 493	"	30 800	80 000	31 100
"	"	89 415	"	31 700	80 000	32 100
"	"	90 560	"	32 200	80 000	32 300
"	"	83 302	"	28 400	60 000	28 400
"	"	83 372	"	28 600	60 000	28 600
"	"	92 680	"	30 900	80 000	30 900
"	"	95 924	"	31 700	80 000	32 100
"	"	89 504	"	32 000	80 000	32 400
"	"	91 813	"	29 600	80 000	30 000
"	"	86 821	"	32 200	80 000	32 300
"	"	81 851	"	28 700	60 000	28 900
"	"	90 634	"	32 300	80 000	32 500
"	"	82 958	"	28 400	60 000	28 400
"	"	91 289	"	29 000	80 000	30 100
"	"	89 443	"	31 800	80 000	32 100
"	"	95 945	"	31 800	80 000	32 000
"	"	94 941	"	31 000	80 000	30 900
"	"	85 915	"	31 600	80 000	31 900
"	"	87 758	"	31 000	80 000	31 800
"	"	91 822	"	30 400	80 000	30 600
"	"	91 482	"	30 300	80 000	30 400
"	"	96 285	"	32 000	80 000	32 000
"	"	83 017	"	27 300	60 000	28 100
"	"	101 052	"	38 500	100 000	39 500
Box	"	82 279	"	28 100	60 000	28 200
"	"	31 042	I. S.	36 300	60 000	36 500
"	"	22 320	I. C.	31 000	60 000	31 500
Gondola	"	6 391	"	24 200	60 000	24 200
"	"	94 066	"	30 500	80 000	31 100
"	"	90 487	"	31 600	80 000	31 900
"	"	86 903	"	31 000	80 000	31 000
"	"	93 952	"	31 400	80 000	31 700
"	"	91 861	"	33 700	80 000	33 100
"	"	86 214	"	30 700	80 000	31 100
"	"	88 076	"	31 700	80 000	31 400
"	"	90 050	"	31 000	80 000	31 000
"	"	85 151	"	31 300	80 000	31 200
"	"	83 526	"	27 300	60 000	27 900
Flat	"	790	"	27 100	80 000	27 000
"	"	1 202	M. C.	28 100	80 000	28 100
"	"	590	C. S. I	27 400	80 000	27 400
"	"	272	C. S. I	24 400	60 000	29 400
"	"	825	M. C.	28 500	80 000	28 400
Caboose	"	98 600	I. C.			40 000

TABLE 10 Tonnage Record

Test No. S-1021

K Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Gondola	L	97 430	I. C.	31 400	100 000	104 600
“	“	95 341	“	30 100	80 000	105 000
“	“	88 198	“	33 000	80 000	98 000
“	“	105 823	“	40 400	100 000	152 000
“	“	90 733	“	31 400	80 000	107 000
“	“	87 110	“	32 000	80 000	108 300
“	“	88 418	“	32 000	80 000	105 600
“	“	84 458	“	30 800	60 000	87 000
“	“	88 321	“	32 600	80 000	109 000
“	“	81 982	“	29 400	60 000	88 000
“	“	91 087	“	30 700	80 000	110 700
“	“	92 434	“	31 400	80 000	106 900
“	“	110 325	“	41 600	100 000	135 800
“	“	3 380	I. S.	40 400	100 000	144 000
“	“	83 881	I. C.	28 900	60 000	87 700
“	“	84 313	“	27 300	60 000	86 000
“	“	92 813	“	30 700	80 000	110 000
“	“	100 242	“	33 100	90 000	124 400
Box	“	47 936	“	39 000	80 000	104 000
“	“	17 469	“	29 000	60 000	70 600
Tank	E	6 355	C. T. L.			38 300
“	“	6 315	“			37 800
Box	L	22 469	I. C.	38 600	80 000	81 700
“	“	9 858	N. C. & St. L.	33 900	60 000	66 200
Gondola	“	104 238	I. C.	40 500	100 000	148 500
“	“	89 092	“	32 500	80 000	115 500
“	“	101 130	“	36 700	100 000	134 700
“	“	82 069	“	29 000	60 000	88 000
“	“	81 382	“	26 900	60 000	83 000
Box	“	130 860	“	42 300	80 000	96 000
“	“	82 292	S. P.	34 200	80 000	75 000
“	“	56 120	C. & N. W.	31 500	50 000	58 000
“	“	12 655	I. C.	29 000	60 000	58 000
Flat	“	66 686	“	28 000	80 000	105 000
“	“	131 191	“	39 500	80 000	95 000
Refrigerator	E	9 547	A. R. L.	38 700	50 000	40 000
Box	L	7 304	H. & T. C.	30 400	60 000	69 000
“	“	130 987	I. C.	42 300	80 000	78 000
Gondola	“	86 023	“	31 200	80 000	118 000
Refrigerator	E	2 130	C. R. D.			41 000
Box	“	74 674	C. & N. W.	34 000	80 000	34 000
Gondola	L	104 603	I. C.	40 500	100 000	149 000
“	“	104 872	“	40 000	100 000	146 000
“	“	105 603	“	40 200	100 000	143 800
Refrigerator	E	6 417	A. R. L.	31 300	50 000	35 800
“	“	50 564	I. C.	35 600	50 000	36 000
Flat	L	807	G. & S. I.	26 400	80 000	61 800
Box	“	39 641	I. C.	36 300	80 000	47 900
Refrigerator	E	3 031	P. B. C.	30 700	40 000	33 700
Box	L	11 344	H. & R.	42 000	100 000	111 200
Gondola	“	87 136	I. C.	31 700	80 000	112 400
“	“	83 896	“	26 600	60 000	86 000
“	“	90 589	“	33 300	80 000	112 000
“	“	87 685	“	31 800	80 000	109 400
“	“	93 498	“	31 000	80 000	107 800
“	“	95 054	“	30 200	80 000	108 000
“	“	100 041	“	34 400	90 000	123 000
“	“	97 555	“	31 800	80 000	99 000
“	“	220	S. L. B. & S.	28 000	60 000	89 000
“	“	95 342	I. C.	29 000	80 000	105 000
“	“	97 459	“	31 400	100 000	103 000
Caboose	E		“			34 000

TABLE 11 Tonnage Record

Test No. S-1023

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Box	L	141 953	I. C.	43 500	100 000	76 000
Gondola	"	104 462	"	40 700	100 000	110 000
"	"	95 110	"	30 000	80 000	83 000
"	"	110 088	"	41 000	100 000	100 000
"	"	95 949	"	30 900	80 000	79 000
Tank	"	59	R. O. R. Co.		80 000	58 000
Box	"	80 880	P. R. R.	33 500	80 000	74 000
"	"	10 951	N. C. & St. L.	32 700	60 000	88 000
"	E	133 684	Southern	33 200	60 000	33 000
Gondola	L	85 410	I. C.	33 300	80 000	93 000
"	"	80 355	"	27 100	60 000	80 000
"	"	90 035	"	29 500	80 000	112 000
Box	"	11 893	L. & N.	30 400	60 000	75 000
Gondola	"	85 248	I. C.	31 000	80 000	112 000
"	"	89 009	"	32 200	80 000	106 000
"	"	94 119	"	31 100	80 000	113 000
"	"	81 946	"	28 400	60 000	96 000
"	"	84 309	"	27 500	60 000	92 000
"	"	88 551	"	32 400	80 000	103 000
"	"	87 027	"	31 700	80 000	95 000
"	"	87 989	"	32 100	80 000	110 000
"	"	90 347	"	33 000	80 000	111 000
"	"	80 226	"	24 700	60 000	80 000
"	"	84 268	"	29 500	60 000	78 000
"	"	100 190	"	34 400	90 000	124 000
"	"	110 196	"	40 800	100 000	133 000
"	"	106 943	"	40 300	100 000	143 000
"	"	80 936	"	27 900	60 000	87 000
"	"	90 907	"	30 900	80 000	108 000
"	"	82 970	"	26 900	60 000	88 000
"	"	104 451	"	40 700	100 000	133 800
"	"	84 142	"	28 200	60 000	89 000
"	"	89 380	"	31 800	80 000	108 000
Box	"	39 074	"	38 300	80 000	94 000
"	"	141 730	"	43 700	100 000	105 000
Refrigerator	E	6 492	N.C. L. C.		60 000	43 000
Box	L	10 019	I. C.	30 800	60 000	36 000
Refrigerator	E	301	U. R. T. Co.	41 100	50 000	39 000
Box	"	155	S. H. C. Co.	40 800	60 000	40 000
"	"	2 056	G. B. & W.	31 400	60 000	31 000
"	"	108 260	Erie	40 100	80 000	38 900
"	L	7 220	I. C.	25 500	50 000	77 800
"	E	28 475	"	36 500	60 000	52 800
Tank	L	708	D. R. & U.			76 000
Box	E	48 782	I. C	39 100	80 000	55 000
Gondola	"	50 861	Erie	40 900	100 000	41 000
"	"	16 977	"	42 800	100 000	42 800
Box	L	141 005	I. C.	43 600	100 000	80 000
Gondola	"	57 131	B. & O.	28 200	60 000	67 000
Box	E	83 308	C. & N. W.	32 600	80 000	32 000
"	"	56 189	U. P.	28 000	50 000	28 000
"	"	78 219	C. & N. W.	34 450	80 000	34 000
"	"	48 596	"	28 300	40 000	28 400
"	"	86	S. H. C. Co.	40 800	60 000	39 000
"	L	13 803	I. C.	29 100	60 000	71 000
"	"	14 437	"	29 500	60 000	65 000
Caboose	E	98 026	"			40 000

TABLE 12 TONNAGE RECORD

Test No. S-1027

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Gondola	L	104 866	I. C.	40 300	100 000	146 700
"	"	104 482	"	36 000	100 000	148 100
"	"	106 662	"	40 200	100 000	146 000
Box	"	15 035	"	29 200	60 000	52 000
"	"	17 391	"	30 000	60 000	59 800
Gondola	"	3 008	I. S.	40 200	100 000	135 400
"	"	609	C. C. & Co.	31 700	80 000	105 900
"	"	622	C. C. & Co.	31 700	80 000	106 500
"	"	92 361	I. C.	33 000	80 000	109 800
"	"	104 423	"	40 900	100 000	139 300
"	"	3 054	I. S.	40 100	100 000	142 400
"	"	105 824	I. C.	40 300	100 000	122 000
"	"	80 466	"	26 700	60 000	84 000
"	"	92 965	"	30 800	80 000	98 000
"	"	94 160	"	31 400	80 000	100 200
"	"	85 775	"	31 200	80 000	100 300
"	"	88 635	"	31 400	80 000	104 400
"	"	83 229	"	27 200	60 000	81 000
"	"	81 193	"	27 300	60 000	83 600
"	"	80 822	"	27 500	60 000	81 900
"	"	104 540	"	40 500	100 000	142 000
"	"	94 317	"	30 800	80 000	108 500
"	"	91 922	"	30 400	80 000	101 800
"	"	91 551	"	28 800	80 000	105 800
"	"	88 090	"	31 500	80 000	101 100
"	"	93 860	"	30 300	80 000	107 100
"	"	80 089	"	28 900	60 000	80 800
"	"	75 482	"	23 000	50 000	65 900
"	"	86 315	"	31 000	80 000	103 200
"	"	629	C. C. & Co.	31 700	80 000	106 500
"	"	76 275	I. C.	24 800	50 000	78 300
"	"	16 225	W. M.	39 100	80 000	117 300
"	"	87 491	I. C.	32 000	80 000	101 800
"	"	93 520	"	29 800	80 000	104 700
Box	"	10 931	T. & N. O.	30 700	60 000	64 100
"	"	21 957	I. C.	38 200	80 000	104 500
Gondola	"	85 133	"	31 500	80 000	62 700
Box	"	33 362	C. & N.	32 400	50 000	38 000
Gondola	"	88 516	I. C.	31 800	80 000	918 000
Box	"	1 614	C. & O.	37 700	80 000	90 100
"	"	7 542	I. C.	28 200	50 000	75 000
"	"	17 356	"	30 100	60 000	73 000
Flat	"	69 086	"	33 100	100 000	75 000
"	E	67 114	"	25 600	80 000	27 600
Caboose	"		"			38 000

TABLE 13 TONNAGE RECORD

Test No. S-1030A

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Gondola	L	110 699	I. C.	41 100	100 000	130 900
"	"	111 182	"	40 700	100 000	129 400
"	"	87 386	"	30 700	80 000	109 300
"	"	3 264	I. S.	40 400	100 000	142 300
"	"	101 209	I. C.	38 100	100 000	145 000
"	"	106 217	"	40 400	100 000	144 500
"	"	25 601	"	31 300	80 000	105 800
"	"	101 160	"	40 200	100 000	145 000
"	"	105 667	"	40 300	100 000	142 600
"	"	101 052	"	38 500	100 000	143 600
"	"	96 213	"	31 900	80 000	106 200
"	"	106 868	"	40 200	100 000	145 200
"	"	81 275	"	29 700	60 000	88 400
"	"	82 959	"	27 900	60 000	87 600
"	"	89 028	"	33 600	80 000	109 600
"	"	81 296	"	28 800	60 000	86 600
"	"	111 248	"	40 800	100 000	133 000
"	"	3 375	I. S.	40 500	100 000	147 000
"	"	104 037	I. C.	40 900	100 000	147 000
"	"	86 480	"	32 000	80 000	119 000
"	"	104 366	"	40 400	100 000	154 800
"	"	92 183	"	31 000	80 000	116 900
"	"	94 862	"	32 600	80 000	117 400
"	"	94 539	"	32 100	80 000	119 200
"	"	104 877	"	40 300	100 000	154 000
"	"	93 341	"	30 700	80 000	118 600
"	"	86 032	"	29 800	80 000	111 500
"	"	89 078	"	31 900	80 000	113 400
"	"	88 556	"	32 200	80 000	110 500
"	"	96 794	"	32 000	100 000	113 000
"	"	88 577	"	32 400	80 000	111 200
"	"	100 243	"	32 800	90 000	125 500
Caboose	E	98 016	"			40 000

TABLE 14 Tonnage Record Test No. S-1030B

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Gondola	L	110 699	I. C.	41 100	100 000	130 900
"	"	111 182	"	40 700	100 000	129 400
"	"	87 386	"	30 700	80 000	109 300
"	"	3 264	I. S.	40 400	100 000	142 300
"	"	101 209	I. C.	38 100	100 000	145 000
"	"	106 217	"	40 400	100 000	144 500
"	"	25 601	"	31 300	80 000	105 800
"	"	101 160	"	40 200	100 000	145 000
"	"	105 667	"	40 300	100 000	142 600
"	"	101 052	"	38 500	100 000	143 600
"	"	96 213	"	31 900	80 000	106 200
"	"	106 868	"	40 200	100 000	145 200
"	"	81 275	"	29 700	60 000	88 400
"	"	82 959	"	27 900	60 000	87 600
"	"	89 028	"	33 600	80 000	109 600
"	"	81 296	"	28 800	60 000	86 600
"	"	111 248	"	40 800	100 000	133 000
"	"	3 375	I S.	40 500	100 000	147 000
"	"	104 037	I. C.	40 900	100 000	147 000
"	"	86 480	"	32 000	80 000	119 000
"	"	104 566	"	40 400	100 000	154 800
"	"	92 183	"	31 000	80 000	116 900
"	"	94 862	"	32 600	80 000	117 400
"	"	94 539	"	32 100	80 000	119 200
"	"	104 877	"	40 300	100 000	154 000
"	"	93 341	"	30 700	80 000	118 600
"	"	86 032	"	29 800	80 000	111 500
"	"	89 078	"	31 900	80 000	113 400
"	"	88 556	"	32 200	80 000	110 500
"	"	96 794	"	32 000	100 000	113 000
"	"	88 577	"	32 400	80 000	111 200
"	"	100 243	"	32 800	90 000	125 500
Box	"	91 482	L. & N.	35 300	65 000	106 100
Gondola	"	66 107	"	37 200	80 000	102 920
Box	E	95 645	M. C.	39 800	60 000	40 000
"	L	13 470	S.	32 600	60 000	50 000
"	"	142 610	I. C.	42 900	100 000	151 900
"	"	14 474	C. N. O. & T. P.	34 800	60 000	71 700
"	"	11 845	L. & N.	30 400	60 000	88 600
Caboose	E	98 016	I. C.			40 000

TABLE 15 Tonnage Record Test No. S-1031

Box	E	34 853	I. C.	37 300	80 000	37 300
"	"	37 120	"	34 300	80 000	34 300
"	"	33 101	"	37 800	80 000	37 900
"	"	11 771	"	29 500	60 000	29 500
"	"	24 366	"	36 500	80 000	36 500
"	"	45 812	"	39 000	80 000	39 000
"	"	35 859	"	36 300	80 000	36 300
"	"	49 227	"	35 600	80 000	35 700
"	"	37 430	"	35 000	80 000	35 100
"	"	48 723	"	39 100	80 000	39 200
"	"	15 256	"	29 500	60 000	29 500
"	"	18 369	"	28 900	60 000	28 800
"	"	46 321	"	37 100	80 000	37 100
"	"	26 699	"	36 300	80 000	36 200
"	"	38 079	"	33 700	80 000	33 700
"	"	49 040	"	38 000	80 000	38 100
"	"	25 514	"	35 500	80 000	35 500
"	"	34 974	"	36 500	80 000	36 600
"	"	24 617	"	35 800	80 000	35 600
"	"	47 800	"	37 700	80 000	37 700
"	"	141 461	"	43 600	100 000	43 600
"	"	140 995	"	42 800	100 000	42 800
"	"	49 435	"	33 800	80 000	33 800
"	"	36 259	"	36 400	80 000	36 400
"	"	16 183	"	30 000	60 000	30 000
"	L	49 414	"	35 300	80 000	59 050
"	"	22 932	"	37 400	80 000	72 900
"	"	19 896	"	29 100	60 000	73 800

TABLE 15—(*Continued*)

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
. .	. .	20 289	. .	28 600	60 000	74 300
. .	. .	15 490	. .	29 900	60 000	73 500
. .	. .	49 183	. .	35 500	80 000	74 100
. .	E	6 909	L. & N.	30 900	60 000	30 700
Gondola	. .	18 273	S.	40 100	100 000	40 300
Box	. .	19 508	St. L. & S. W.	32 000	60 000	32 100
Flat	. .	66 887	I. C.	27 600	80 000	27 300
Caboose	. .	98 119	. .			40 000

TABLE 16 Tonnage Record Test No. S-1033

Test	E	17				58 000
Gondola	L	49 085	N. & W.	37 900	80 000	124 000
. .	. .	731	C. C. & Co.	31 700	80 000	110 000
. .	. .	708	. .	31 600	80 000	104 600
. .	. .	619	. .	31 700	80 000	104 000
. .	. .	742	. .	31 700	80 000	108 300
. .	. .	748	. .	31 700	80 000	104 300
. .	. .	104 775	I. C.	40 300	100 000	132 400
. .	. .	104 149	. .	40 700	100 000	133 100
. .	. .	83 232	. .	28 300	60 000	88 900
. .	. .	12 076	D	33 500	80 000	97 100
. .	. .	89 448	I. C.	31 800	80 000	109 000
. .	. .	89 505	. .	32 500	80 000	106 400
. .	. .	47 043	N. & W.	32 000	85 000	99 000
. .	. .	79 189	I. C.	24 500	50 000	72 700
. .	. .	666	L . . A. & W.	40 600	60 000	92 800
. .	. .	115 003	I. C.	43 000	100 000	122 300
. .	. .	85 906	. .	34 600	80 000	113 000
. .	. .	83 928	. .	26 500	60 000	77 000
. .	. .	106 446	. .	39 600	100 000	133 100
. .	. .	104 846	. .	40 200	100 000	142 000
. .	. .	86 763	. .	32 100	80 000	104 000
. .	. .	97 319	. .	32 900	100 000	98 000
. .	. .	97 061	. .	31 900	100 000	101 000
. .	. .	81 968	. .	26 400	60 000	88 100
. .	. .	707	C. C. Co,	31 700	80 000	107 000
. .	. .	94 140	I. C.	31 600	80 000	98 000
. .	. .	88 213	. .	31 900	80 000	105 000
. .	. .	86 642	. .	31 300	80 000	106 000
. .	. .	111 336	. .	40 100	100 000	126 000
. .	. .	80 952	. .	26 000	60 000	84 000
. .	. .	79 077	. .	34 900	50 000	82 000
. .	. .	14 722	M. & O.	33 900	80 000	95 100
. .	. .	106 167	I. C.	40 300	100 000	136 000
. .	. .	90 535	. .	32 700	80 000	102 000
. .	. .	93 442	. .	29 500	80 000	104 600
. .	. .	16 738	Erie	42 800	100 000	102 800
. .	. .	85 379	I. C.	31 200	80 000	110 900
. .	. .	87 672	. .	31 300	80 000	104 000
. .	. .	30 456	C. & B.	39 100	100 000	128 000
. .	. .	80 855	I. C.	28 300	60 000	86 100
. .	. .	85 959	. .	31 000	80 000	103 100
. .	. .	644	C. C. Co.	31 700	80 000	106 100
Caboose	E	19 510	I. C.			40 000

TABLE 17 TONNAGE RECORD Test No. S-1034

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Gondola	E	80 223	I. C.	26 900	60 000	25 200
"	"	89 617	"	32 200	80 000	32 400
"	"	110 863	"	41 000	100 000	41 200
"	"	34 775	N. Y. C.	41 600	100 000	41 700
"	"	86 158	I. C.	31 300	80 000	31 100
"	"	80 338	"	24 500	60 000	23 900
"	"	87 806	"	31 500	80 000	31 500
"	"	96 249	"	30 900	80 000	30 500
"	"	9 038	T, & O. C.	26 700	60 000	24 500
"	"	79 089	I. C.	23 200	50 000	23 300
"	"	93 123	"	31 100	80 000	31 800
"	"	82 546	"	27 900	60 000	27 500
"	"	104 295	"	40 500	100 000	40 400
"	"	89 543	"	30 900	80 000	31 300
"	"	110 722	"	41 500	100 000	41 700
"	"	92 260	"	31 100	80 000	30 500
"	"	84 227	"	28 400	60 000	27 200
"	"	81 254	"	27 400	60 000	26 700
"	"	85 110	"	31 400	80 000	30 400
"	"	105 192	"	40 300	100 000	40 200
"	"	15 248	Van. Line	40 700	100 000	40 600
"	"	92 465	I. C.	31 200	80 000	30 200
"	"	90 716	"	31 400	80 000	30 700
"	"	800 312	Penn.	38 400	100 000	38 300
"	"	3 190	I. S.	40 600	100 000	40 400
"	"	47 608	N. & W.	32 600	85 000	34 000
"	"	93 502	I. C.	30 100	80 000	30 400
"	"	105 620	"	40 300	100 000	40 100
"	"	85 250	"	30 400	80 000	30 900
"	"	90 396	"	31 000	80 000	30 900
"	"	3 183	I. S.	40 400	100 000	40 600
"	"	96 492	I. C.	31 000	80 000	30 300
"	"	104 730	"	40 400	100 000	40 500
"	"	104 667	"	40 700	100 000	40 600
"	"	94 692	"	32 000	80 000	32 100
"	"	82 744	"	27 900	60 000	28 600
"	"	282 388	Penn.	45 000	100 000	40 400
"	"	94 128	I. C.	30 300	80 000	30 100
"	"	94 783	"	31 200	80 000	30 900
"	"	104 702	"	40 600	100 000	40 500
"	"	96 797	"	31 400	100 000	33 200
"	"	96 917	"	30 200	80 000	30 200
"	"	106 219	"	40 300	100 000	40 200
"	"	28 743	C. & O.	39 900	100 000	38 700
"	"	83 171	I. C.	28 400	60 000	27 200
"	"	96 089	"	31 000	80 000	31 000
"	"	49 415	N. & W.	38 200	100 000	37 100
"	"	93 048	I. C.	31 600	80 000	31 000
"	"	13 930	C. & O.	25 000	60 000	25 300
"	"	13 648	N. & W.	34 100	80 000	34 000
"	"	29 059	C. & O.	41 400	100 000	41 000
"	"	14 840	"	30 900	80 000	30 300
"	"	76 008	I. C.	24 300	50 000	23 000
"	"	86 763	"	32 100	80 000	30 700
"	"	83 969	"	26 200	60 000	27 200
"	"	88 028	"	30 400	80 000	31 400
"	"	89 502	"	31 800	80 000	31 500
"	"	806 908	"	40 200	100 000	40 100
"	"	68 698	L. & N.	35 400	80 000	35 500
"	"	81 422	I. C.	26 800	60 000	27 000
"	"	106 388	"	40 800	100 000	40 800
"	"	11 625	C. & E. I.	32 400	80 000	31 000
"	"	75 084	"	38 400	100 000	38 900
"	"	3 393	I. S.	40 100	100 000	40 000
"	"	105 811	I. C.	40 400	100 000	40 800
"	"	91 161	"	30 000	80 000	29 600
"	"	27 237	Big Four	22 500	50 000	24 600
"	"	33 336	L. & N.	28 400	66 000	28 500
"	"	91 941	I. C.	33 000	80 000	31 300
"	"	106 191	"	40 000	100 000	40 200
"	"	78 930	"	25 200	50 000	23 500
"	"	85 198	"	31 300	80 000	30 500
"	"	91 102	"	31 300	80 000	29 700
"	"	32 243	L. & N.	30 400	66 000	30 200
"	"	41 069	N. & W.	38 100	100 000	38 000
Caboose	"	98 465	I. C.			40 000

TABLE 18 TONNAGE RECORD

Test No. S-1036

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Test	E	17				58 000
Flat	L	65 913	I. C.	27 900	80 000	79 600
Gondola	"	81 595	"	27 500	60 000	90 000
"	"	97 929	"	31 100	80 000	98 000
"	"	95 885	"	31 000	80 000	106 000
"	"	87 632	"	31 700	80 000	108 400
"	"	96 914	"	31 900	100 000	105 000
"	"	76 735	"	25 200	50 000	78 000
"	"	84 272	"	37 500	60 000	76 000
"	"	91 429	"	33 000	80 000	106 000
"	"	89 678	"	32 400	80 000	110 100
Box	"	13 664	W. C.	29 000	60 000	32 100
Refrigerator	"	55 059	I. C.	36 900	60 000	38 400
Box	E	14 010	N. Y. C.	33 600	30 000	31 000
"	L	21 307	I. C.	37 500	80 000	56 300
"	E	41 633	P. M.	34 500	60 000	35 600
"	L	18 103	C. B. & Q.	25 200	40 000	64 000
"	"	131 327	I. C.	39 700	80 000	91 400
"	"	122 440	C. S, N. O. & P.	39 500	80 000	109 100
"	"	8 116	St. J. & G. I.	35 400	80 000	73 800
"	"	39 116	I. C.	36 300	80 000	111 600
"	"	141 137	"	43 100	100 000	64 300
"	"	12 971	"	30 200	60 000	46 000
"	"	7 198	Big Four	31 200	60 000	93 500
"	"	19 591	M. & O.	33 700	60 000	88 200
"	"	18 581	"	33 500	60 000	91 500
"	"	9 593	"	31 200	60 000	83 600
"	"	9 224	C. I. & L.	29 800	50 000	73 100
"	"	11 136	M. C. & St. L.	34 000	60 000	67 700
"	E	64 614	C. & N. W.	30 100	60 000	29 400
"	L	5 251	N. C. & St. L.	29 500	60 000	93 400
"	"	6 714	"	29 600	60 000	69 800
"	"	49 041	I. C.	39 100	80 000	106 800
Gondola	"	95 823	"	31 600	80 000	74 000
Refrigerator	E	5 773	Armour	38 700	50 000	39 600
Box	L	6 692	I. C.	26 800	50 000	72 000
"	"	6 609	T. St. L. & W.	38 100	80 000	82 100
"	"	28 434	N. Y. C.	35 800	80 000	81 000
"	"	14 257	Penn.	44 400	100 000	98 000
"	"	40 571	M. & O.	34 600	60 000	90 000
Gondola	"	85 836	I. C.	30 500	80 000	60 000
Box	"	11 615	"	29 800	60 000	111 000
"	"	13 534	Q. & C.	33 800	60 000	80 000
"	"	42 169	I. C.	33 400	60 000	76 100
"	E	27 093	L. S. & M. S.	29 300	60 000	29 000
"	L	10 859	I. C.	30 000	60 000	66 400
"	"	141 286	"	42 600	100 000	106 200
Gondola	"	3 218	I. S.	40 300	100 000	91 400
Box	"	13 675	I. C.	29 800	60 000	46 000
Gondola	"	93 300	"	31 900	80 000	74 100
Refrigerator	E	55 987	"	38 600	60 000	39 400
Caboose	"	98 040	"			40 000

TABLE 19 TONNAGE RECORD

Test No. S-1038

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Test	E	17				58 000
Gondola	L	91 059	I. C.	29 400	80 000	115 000
"	"	106 262	"	40 300	100 000	136 000
"	"	106 565	"	40 300	100 000	134 000
Box	"	142 548	"	42 900	100 000	91 800
Gondola	"	730	C. C. & Co.	30 900	80 000	103 300
"	"	84 047	I. C.	28 500	60 000	85 300
"	"	88 999	"	32 200	80 000	105 000
"	"	85 215	"	31 600	80 000	102 700
"	"	82 640	"	27 600	60 000	81 300
"	"	81 883	"	28 800	60 000	80 000
"	"	76 477	"	23 300	50 000	75 500
"	"	93 590	"	29 800	80 000	107 300
"	"	90 934	"	31 000	80 000	104 800
"	"	93 342	"	32 500	80 000	104 500
"	"	102 091	"	37 300	80 000	120 000
"	"	31 063	C. & O.	39 200	100 000	138 000
"	"	85 304	I. C.	31 500	80 000	111 500
"	"	26 505	C. & O.	38 100	100 000	130 200
"	"	110 803	I. C.	41 100	100 000	135 500
"	"	104 015	"	40 500	100 000	146 500
"	"	105 581	"	40 400	100 000	139 000
"	"	104 984	"	40 500	100 000	146 100
"	"	91 126	"	30 600	80 000	104 000
"	"	88 342	"	31 800	80 000	105 000
"	"	93 901	"	31 500	80 000	103 400
"	"	81 303	"	28 100	60 000	85 000
"	"	44 086	N. & W.	38 300	100 000	129 300
"	"	104 532	I. C.	40 600	100 000	142 300
"	"	15 820	M. & O.	34 100	80 000	104 600
"	"	106 646	I. C.	40 400	100 000	143 800
"	"	88 819	"	31 600	80 000	104 600
"	"	104 584	"	40 400	100 000	152 000
"	"	3 160	I. S.	40 300	100 000	154 000
Box	"	87 344	B. & O.	30 400		73 300
"	"	704	W. H. & D.		60 000	41 000
"	E	12 694	W. C.	29 100	60 000	28 900
"	L	19 705	I. C.	29 600	60 000	74 300
"	"	16 310	"	29 800	60 000	59 600
"	"	12 417	"	29 900	60 000	91 400
Caboose	E	98 090	"			40 000

TABLE 20 TONNAGE RECORD

Test No. S-1040

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Test	E	17				58 000
Box	L	98 633	C. B. & Q.	34 300	80 000	54 900
Gondola	"	106 306	I. C.	40 800	100 000	138 500
"	"	106 368	"	40 400	100 000	146 500
"	"	94 314	"	29 000	80 000	105 600
Box	"	39 814	"	37 100	80 000	121 000
Gondola	"	86 947	"	31 100	80 000	110 000
"	"	16 683	H. V. Y.	32 800	80 000	110 700
"	"	97 659	I, C.	30 200	80 000	99 300
Box	"	78 121	B. & O.	31 600	60 000	70 200
Gondola	"	90 363	I. C.	33 600	80 000	95 600
"	"	13 381	N. & W.	34 100	80 000	107 600
Box	"	35 061	St. L. & S. F.	35 100	60 000	82 200
"	"	17 339	I. C.	28 600	60 000	62 000
"	"	37 489	"	33 500	80 000	71 200
Tank	"	505	F. O. Co.		60 000	88 900
Box	"	25 394	V. S. & P	32 200	60 000	80 400
"	"	131 417	I. C.	39 900	80 000	64 500
"	"	39 626	"	36 200	80 000	79 000
Gondola	"	92 487	"	30 000	80 000	110 600
Box	"	91 157	L. & N.	33 200	65 000	86 500
Gondola	"	89 843	I. C.	30 900	80 000	86 600
Box	"	4 931	N. & S.	32 200	60 000	74 300
Gondola	"	5 642	K. & M.	32 500	80 000	91 600
"	"	93 209	I. C.	32 800	80 000	110 000
Box	"	34 736	"	36 400	80 000	56 300
"	"	101 264	C. B. & Q.	35 000	80 000	60 000
"	"	32 412	C. R. I. & P.	38 900	80 000	67 900
"	"	10 137	N. C. & St. L.	33 400	80 000	80 300
Gondola	"	94 256	I. C.	30 000	80 000	78 800
Box	"	3 467	L. E. & St. L.	34 300	60 000	101 000
"	"	11 192	S.	30 900	60 000	75 800
"	"	46 541	I. C.	38 000	80 000	67 100
Gondola	"	86 513	"	31 200	80 000	125 800
"	"	89 288	"	31 800	80 000	95 800
"	"	105 949	"	40 300	100 000	145 600
"	"	91 129	"	28 800	80 000	108 100
"	"	85 020	"	31 400	80 000	108 900
"	"	95 929	"	29 900	80 000	124 000
"	"	12 555	C. & O.	30 900	80 000	115 800
"	"	96 796	I. C.	31 900	100 000	114 300
"	"	84 200	"	27 400	60 000	80 000
"	"	27 738	H. V.	40 700	100 000	147 900
Box	"	30 778	S. P.	34 000	80 000	85 200
"	"	49 450	I. C.	35 300	80 000	67 700
"	"	17 968	"	31 200	80 000	52 300
Caboose	E		"			40 000

TABLE 21 TONNAGE RECORD

Test No. S-1043

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Gondola	E	95 986	I. C.	30 600	80 000	30 600
"	"	101 110	"	38 400	100 000	38 400
"	"	5 968	P. & L. E.	34 300	80 000	34 300
Box	"	37 982	I. C.	37 300	80 000	37 300
"	"	15 601	"	29 300	60 000	29 300
"	"	19 314	"	29 900	60 000	29 900
"	"	12 938	"	29 600	60 000	29 600
"	"	17 905	"	30 100	60 000	30 100
"	"	14 809	"	30 400	60 000	30 400
"	"	37 132	"	33 000	80 000	33 000
"	"	11 765	"	29 900	60 000	29 900
"	"	23 243	"	33 800	80 000	33 800
"	"	41 230	"	32 900	50 000	32 900
"	"	37 957	"	33 000	80 000	33 000
"	"	35 762	"	35 600	80 000	35 600
"	"	36 298	"	36 400	80 000	36 400
"	"	15 281	"	30 400	60 000	30 400
Tank	L	489	A. T. L.	38 000	65 000	102 900
Gondola	E	643	C. C. & C.	31 700	80 000	31 700
"	"	641	"	31 700	80 000	31 700
"	"	182 400	C. I. & S.	31 000	80 000	31 000
"	"	82 014	I. C.	26 500	60 000	26 500
"	"	638	C. C. & C.	31 700	80 000	31 700
"	"	19 570	C. & A.	37 200	100 000	37 200
"	"	89 865	I. C.	31 700	80 000	31 700
"	"	105 764	"	40 400	100 000	40 400
"	"	92 517	"	32 000	80 000	32 000
"	"	3 303	I. S.	40 200	100 000	40 200
"	"	97 056	I. C.	32 500	100 000	32 500
"	"	83 510	"	28 400	60 000	28 400
"	"	97 836	"	30 900	80 000	30 900
"	"	89 837	"	32 200	80 000	32 200
"	"	81 684	"	30 700	60 000	30 700
"	"	115 302	"	42 600	100 000	42 600
"	"	81 483	"	28 000	60 000	28 000
"	"	87 171	"	31 500	80 000	31 500
"	"	25 359	P & R.	33 200	100 000	31 200
"	"	95 635	I. C.	30 200	80 000	30 200
"	"	92 911	"	31 200	80 000	31 200
"	"	88 752	"	32 000	80 000	32 000
"	"	25 900	H. V.	33 100	80 000	33 100
"	"	85 502	I. C.	31 500	80 000	31 500
"	"	89 559	"	31 900	80 000	31 200
"	"	93 107	"	31 800	80 000	31 800
"	"	81 999	"	28 300	60 000	28 700
"	"	104 780	"	40 300	100 000	40 300
"	"	93 305	"	31 200	80 000	31 200
"	"	110 801	"	41 100	100 000	41 100
"	"	97 203	"	30 200	100 000	30 200
"	"	93 068	"	31 200	80 000	31 200
"	"	91 183	"	30 900	80 000	30 000
"	"	86 323	"	30 100	80 000	30 100
"	"	85 904	"	31 600	80 000	31 600
"	"	95 984	"		80 000	32 100
"	"	93 093	"	32 000	80 000	32 000
"	"	89 480	"	30 800	80 000	30 800
"	"	111 066	"	41 100	100 000	41 100
"	"	111 012	"	41 200	100 000	41 900
"	"	97 889	"	31 400	80 000	31 400
"	"	96 577	"	32 400	100 000	32 400
"	"	97 927	"	32 000	80 000	32 000
"	"	90 488	"	30 600	80 000	30 600
"	"	9 548	T. & O. C.	26 300	60 000	26 300
"	"	111 311	I. C.	40 800	100 000	40 800
Box	"	6 498	N. C, & St. L.	29 200	60 000	29 200
Caboose	"	98 185	I. C.	40 000		40 000

TABLE 22 Tonnage Record

Test No. S-1048

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Test	E	17				58 000
Box	L	98 252	N. Y. C.&H. R.	35 600	80 000	43 500
Gondola	"	106 449	I. C.	40 300	100 000	140 000
"	"	18 867	C. H. & D.	30 200	70 000	97 200
"	"	15 342	C. & O.	30 700	85 000	78 300
"	"	104 271	I. C.	40 600	100 000	146 500
"	"	68 282	L. & N.	36 800	80 000	120 000
"	"	10 579	I. C.	41 200	100 000	134 300
"	"	83 518	"	27 000	60 000	82 600
"	"	95 129	"	31 200	80 000	107 900
"	"	93 198	"	30 600	80 000	105 000
"	"	96 507	"	32 300	100 000	111 000
"	"	93 807	"	29 300	80 000	107 800
"	"	106 189	"	40 400	100 000	142 100
"	"	111 300	"	40 800	100 000	124 200
"	"	105 618	"	40 300	100 000	106 600
"	"	91 108	"	29 900	80 000	108 500
Box	"	2 059	C. P. T.	30 800	60 000	90 800
Gondola	"	84 458	I. C.	30 800	60 000	92 400
"	"	87 958	"	31 800	80 000	109 000
"	"	295 924	P.	40 800	100 000	125 400
"	"	28 318	C & O		100 000	144 200
"	"	82 790	I. C.	31 400	60 000	86 400
"	"	86 569	"	30 600	80 000	107 700
"	"	87 485	"	33 000	80 000	108 600
"	"	94 069	"	31 000	80 000	107 400
"	"	89 271	"	32 000	80 000	109 200
"	"	81 366	"	29 100	60 000	84 200
"	"	95 850	"	30 500	80 000	104 600
"	"	110 910	"	40 800	100 000	140 800
"	"	96 255	"	31 000	80 000	105 000
"	"	94 541	"	31 400	80 000	107 600
"	"	83 229	"	27 000	60 000	85 000
"	"	95 820	"	30 800	80 000	100 000
"	"	82 045	"	28 900	60 000	87 300
"	"	94 443	"	30 300	80 000	105 300
"	"	106 431	"	40 400	100 000	121 600
Box	"	16 036	"	30 800	60 000	80 400
"	E	6 672	A. R. L.	31 500	50 000	33 600
"	"	5 284	"	32 800	50 000	39 400
"	"	9 851	"	39 400	50 000	39 800
"	"	7 342	S.			39 500
"	"	10 458	A.	39 500	60 000	39 600
"	L	8 969	A. R. L.	34 000	50 000	42 100
"	E	352	U. R. T.	42 000	50 000	47 300
"	L	141 533	I. C.	43 700	100 000	96 600
"	"	66 182	C. & N. W.	30 000	60 000	65 300
"	"	28 208	I. C.	35 500	60 000	68 500
"	"	13 088	C. G. W.	30 000	60 000	58 700
"	"	16 008	C. B.	32 000	60 000	58 500
"	"	41 753	P. M.	36 700	60 000	64 300
"	"	13 494	I. C.	31 100	60 000	72 200
"	"	19 247	"	29 600	60 000	63 900
Caboose	E	98 098	"			40 000

TABLE 23 Tonnage Record

Test No. S-1050

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Box	L	34 403	I. C.	36 800	80 000	124 900
"	"	13 317	"	30 100	60 000	81 000
"	"	11 385	"	29 200	60 000	91 800
"	"	140 166	"	42 800	100 000	139 500
"	"	42 477	"	34 400	60 000	84 200
"	"	36 731	"	33 700	80 000	100 900
"	"	39 317	"	37 500	80 000	125 200
"	"	25 435	"	36 600	80 000	119 500
"	E	31 909	T. R. E.	32 100	50 000	34 800
"	L	25 238	I. C.	36 900	80 000	119 300
"	"	45 799	"	41 400	80 000	105 200
"	E	12 043	O. N. & T. P.	33 550	60 000	33 500
"	L	36 163	I. C.	36 800	80 000	121 600
"	"	24 790	"	35 800	80 000	120 800
"	"	6 364	"	27 600	50 000	82 400
"	"	14 070	"	31 600	60 000	100 300
"	"	15 686	"	30 300	60 000	97 000
"	"	35 619	"	36 500	80 000	126 800
"	"	15 962	"	30 400	60 000	88 800
"	"	141 521	"	43 600	100 000	142 400
"	"	130 492	"	40 100	80 000	120 800
"	"	45 566	"	38 500	80 000	119 900
"	"	131 556	"	39 000	80 000	97 600
"	"	21 716	"	37 800	80 000	105 600
"	"	46 134	"	40 700	80 000	127 700
"	"	39 374	"	37 900	80 000	125 200
"	E	31 415	T. R. E.	32 400	50 000	32 400
"	"	31 968	"	32 100	50 000	33 000
"	"	31 395	"	34 100	50 000	34 800
Gondola	"	94 837	I. C.	32 800	80 000	32 800
"	"	110 177	"	41 200	100 000	41 200
"	"	3 170	I. S.	38 200	100 000	38 200
"	"	91 705	I. C.	29 700	80 000	29 700
"	"	90 682	"	30 700	80 000	30 700
"	"	86 138	"	30 100	80 000	30 100
"	"	104 281	"	40 700	100 000	40 700
"	"	104 495	"	40 700	100 000	40 700
"	"	107 359	"	39 600	100 000	39 600
"	"	110 117	"	41 700	100 000	41 700
Caboose	"	98 197	"			34 000

TABLE 24 TONNAGE RECORD

Test No. S-1052

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Gondola	E	91 208	I. C.	30 200	80 000	30 200
"	"	83 764	"	26 800	60 000	26 800
"	"	252	S. S. C.	25 500	50 000	25 800
"	"	89 137	I. C.	31 200	80 000	31 300
"	"	83 992	"	28 200	60 000	28 400
"	"	112 770	"	43 500	100 000	43 500
"	"	81 989	"	28 900	50 000	28 900
"	"	94 688	"	31 100	80 000	31 300
"	"	101 073	"	38 200	100 000	38 200
"	"	3 351	I. S.	40 700	100 000	40 800
"	"	106 100	I. C.	40 200	100 000	40 200
"	"	106 314	"	40 300	100 000	40 200
"	"	82 600	"	26 800	60 000	27 000
"	"	91 316	"	30 200	80 000	30 500
"	"	722	C. C. & Co.	31 700	80 000	31 200
"	"	91 162	I. C.	29 700	80 000	30 100
"	"	107 030	"	39 800	100 000	39 800
"	"	641	C. C. & Co.	31 700	80 000	31 500
"	"	80 993	I. C.	23 600	60 000	26 500
Box	"	11 116	F. G. E.	36 500	50 000	33 200
"	"	11 050	"	36 500	50 000	34 600
"	"	31 153	T. R. E.	32 300	50 000	34 000
"	"	31 286	"	31 500	50 000	34 200
"	"	11 243	N. C. & St. L.	33 600	60 000	33 500
"	"	15 945	Air Line	34 600	60 000	34 800
"	"	827	D. S. D.	35 500	50 000	37 800
"	"	133 280	S.	33 500	60 000	32 800
"	"	33 886	C. of N. J.	30 500	60 000	30 600
"	L	24 968	I. C.	36 000	80 000	119 500
"	"	39 671	"	36 300	80 000	118 100
"	"	21 633	"	38 400	80 000	122 500
"	"	131 151	"	38 900	80 000	129 600
"	"	13 792	"	29 800	60 000	92 300
"	"	45 456	"	38 800	80 000	98 000
"	"	47 105	"	40 100	80 000	100 200
"	"	20 336	"	28 600	60 000	89 000
"	"	13 831	"	29 900	60 000	89 000
"	E	25 361	V. S. & P.	31 800	60 000	31 800
"	"	31 199	T. R. E.	32 150	50 000	34 800
"	"	30 283	"	38 700	50 000	36 000
Gondola	L	92 708	I. C.	32 000	80 000	84 000
"	"	112 608	"	43 500	100 000	88 400
Box	"	580 498	U. L.	30 500	60 000	53 500
"	E	30 562	S.	35 600	60 000	35 400
Gondola	L	92 748	I. C.	30 400	80 000	74 000
Box	E	25 391	V. S. & P.	32 200	60 000	32 400
"	"	17 212	L. & N.	31 200	60 000	31 700
"	"	35 863	S.	35 900	60 000	35 800
"	"	37 798	S.	35 200	60 000	35 800
"	L	130 809	I. C.	40 200	80 000	97 800
Gondola	"	94 511	"	31 000	80 000	37 800
Box	"	141 249	"	43 500	100 000	82 800
"	"	39 219	"	36 300	80 000	79 000
"	E	25 618	A. C. L.	34 960	60 000	34 700
"	"	19 314	St. L. S W.	32 700	60 000	32 800
"	"	85 683	S. P.	42 600	100 000	43 500
"	"	10 255	N. C. & St. L.	32 900	60 000	34 000
"	"	5 803	L. & N.	30 500	60 000	30 000
"	"	20 864	S.	32 800	60 000	35 100
Flat	"	10 016	N. O. & N. E.	27 200	80 000	27 000
Caboose	"	98 093	I. C.			34 000

TABLE 25 TONNAGE RECORD

Test No. S-1057

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Box	L	12 269	C. N. O. & T. P.	33 600	60 000	89 300
Gondola	"	91 889	I. C.	29 500	80 000	107 400
"	"	83 859	"	27 200	60 000	87 800
"	"	83 709	"	28 000	60 000	88 200
"	"	94 023	"	30 600	80 000	102 200
"	"	97 927	"	32 000	80 000	100 600
Box	"	46 152	"	40 000	80 000	58 700
Gondola	"	93 980	"	30 700	80 000	105 400
"	"	91 254	"	29 400	80 000	110 800
Box	"	6 750	"	26 400	50 000	68 600
"	E	57 408	N. Y. C. & H. R.	31 000	60 000	36 100
"	L	108 212	Erie	39 900	80 000	69 700
Tank	"	628	D. R. & U.			68 200
Gondola	"	91 422	I. C.	30 000	80 800	105 600
Box	E	D27 572	L. S. & M. S.	28 800	60 000	33 400
"	L	15 891	I. C.	28 700	60 000	70 300
"	"	11 267	"	28 400	60 000	81 100
"	"	33 918	"	37 900	80 000	80 300
Gondola	"	106 527	"	40 200	100 000	142 800
"	"	104 823	"	40 300	100 000	145 100
"	"	91 474	"	29 900	80 000	112 800
"	"	82 786	"	26 900	60 000	86 700
"	"	607	C. C. & C.	31 700	80 000	107 800
"	"	106 577	I. C	40 300	100 000	144 400
"	"	106 447	"	40 400	100 000	142 900
Box	"	130 255	"	41 000	80 000	90 300
"	"	7 086	"	26 600	50 000	69 000
Flat	"	67 554	"	28 800	80 000	56 200
Box	"	39 223	"	37 500	80 000	72 800
"	"	21 181	"	37 500	80 000	85 800
"	E	515 733	P. F. W. C.	43 800	100 000	41 200
"	L	29 516	I. C.	39 800	60 000	73 000
Flat	"	2 292	G. C.	23 500	60 000	79 200
Gondola	"	105 859	I. C.	40 400	100 000	146 200
"	"	86 778	"	31 000	80 000	115 100
"	"	112 241	"	36 500	80 000	96 300
Box	"	15 982	"	30 400	60 000	80 000
Gondola	E	189	C. & I. W.	32 700	90 000	33 100
"	"	7 162	N. Y. C. & St. L.	31 700	80 000	31 000
"	L	91 371	I. C.	30 400	80 000	80 600
Flat	"	814	G. & S. I.	26 600	80 000	85 800
Box	"	15 282	I. C.	29 400	60 000	67 400
"	E	1 695	A. R.	28 200	50 000	31 200
"	L	15 427	I. C.	30 000	60 000	67 800
"	"	24 933	"	35 000	80 000	102 000
"	"	27 737	B.	29 500	60 000	61 200
"	"	40 712	M. & O.	34 500	60 000	72 800
Gondola	"	85 879	I. C.	30 500	80 000	79 600
Box	"	36 585	"	36 000	80 000	58 200
Caboose	E	98 565	"			34 000

TABLE 26 TONNAGE RECORD

Test No. S-1061

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Gondola	L	88 518	I. C.	32 200	80 000	107 400
"	"	106 156	"	38 400	100 000	146 000
"	"	106 707	"	40 500	100 000	144 600
"	"	94 475	"	31 100	80 000	109 200
"	"	81 333	"	27 300	60 000	82 300
"	"	86 360	"	31 900	80 000	104 300
"	"	95 040	"	30 400	80 000	106 600
"	"	101 029	"	37 500	100 000	138 600
"	"	112 734	"	43 500	100 000	112 600
"	"	81 632	"	26 200	60 000	85 200
"	"	87 626	"	31 700	80 000	103 700
"	"	80 610	"	27 200	60 000	82 400
"	"	94 976	"	31 400	80 000	119 000
"	"	88 425	"	31 400	80 000	118 000
"	"	95 299	"	30 500	80 000	101 200
"	"	628	C. C. & Co.	31 700	80 000	110 400
"	"	95 250	I. C.	30 300	80 000	112 000
"	"	88 750	"	31 900	80 000	112 200
"	"	276	S. C. Co.	30 700	80 000	112 000
"	"	205	S. S. C. Co.	26 500	60 000	82 700
"	"	254	"	26 500	50 000	80 000
"	"	208	"	26 500	60 000	81 300
"	"	256	"	25 500	50 000	80 000
"	"	88 256	I. C.	32 000	80 000	107 700
"	"	104 074	"	40 600	100 000	138 400
"	"	93 754	"	29 600	80 000	104 400
"	"	92 486	"	30 500	80 000	102 000
"	"	106 300	"	40 200	100 000	147 300
"	"	104 742	"	40 300	100 000	146 000
"	"	106 846	"	40 500	100 000	141 000
"	"	11 247	"	40 900	100 000	134 900
"	"	111 175	"	40 700	100 000	136 900
"	"	84 467	"	30 400	60 000	96 200
"	"	90 399	"	31 000	80 000	108 600
"	"	82 953	"	28 000	60 000	91 200
"	"	86 147	"	31 200	80 000	103 500
"	"	107 646	"	39 500	100 000	137 900
Flat	"	6 708	"	27 900	60 000	81 800
"	E	3 736	A. C. L.	31 700	40 000	31 700
"	L	6 719	"	27 900	60 000	74 400
"	"	6 455	"	26 400	60 000	66 400
"	E	8 494	H. & H.	28 800	80 000	30 300
Caboose	"	98 155	I. C.			34 000

TABLE 27 Tonnage Record

Test No. S-1063

Kind of Car	Loaded or Empty	Car No.	Car Intial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Box	L	22 195	I. C.	37 800	80 000	115 400
"	"	46 472	"	36 500	80 000	127 300
"	"	17 530	"	28 600	60 000	95 200
"	"	49 063	"	37 200	80 000	125 300
Gondola	E	112 486	"	43 400	100 000	43 400
"	"	112 463	"	43 700	100 000	43 700
"	"	112 300	"	36 500	80 000	36 500
"	"	112 527	"	43 400	100 000	43 400
"	"	112 515	"	43 500	100 000	43 500
"	"	112 428	"	43 300	100 000	43 300
"	"	112 407	"	43 600	100 000	43 600
"	"	112 679	"	43 300	100 000	43 300
"	"	112 403	"	43 500	100 000	43 500
"	"	112 775	"	43 600	100 000	43 600
"	"	112 585	"	43 400	100 000	43 400
"	"	92 756	"	30 500	80 000	30 500
"	"	88 647	"	31 500	80 000	31 500
"	"	82 152	"	26 600	60 000	26 600
"	"	112 633	"	43 500	100 000	43 500
"	"	112 578	"	43 400	100 000	43 400
"	"	112 596	"	43 700	100 000	43 700
"	"	112 685	"	43 600	100 000	43 600
"	"	112 549	"	43 400	100 000	43 400
"	"	112 502	"	43 400	100 000	43 400
"	"	112 724	"	43 500	100 000	43 500
"	"	112 481	"	43 200	100 000	43 200
"	"	112 709	"	43 400	100 000	43 400
"	"	112 494	"	43 800	100 000	43 800
"	"	112 684	"	43 600	100 000	43 600
"	"	106 653	"	40 300	100 000	40 300
"	"	87 789	"	31 300	80 000	31 300
"	"	82 875	"	28 400	60 000	28 400
"	"	95 097	"	30 200	80 000	30 200
"	"	92 650	"	30 000	80 000	30 000
"	"	93 464	"	30 000	80 000	30 000
"	"	89 101	"	31 600	80 000	31 600
"	"	90 956	"	31 400	80 000	31 400
"	"	86 615	"	30 500	80 000	30 500
"	"	96 487	"	30 600	80 000	30 600
"	"	110 780	"	41 000	100 000	41 000
"	"	86 267	"	31 200	80 000	31 200
"	"	111 294	"	41 100	100 000	41 100
"	"	95 713	"	32 700	80 000	32 700
"	"	88 462	"	32 200	80 000	32 200
"	"	88 685	"	30 800	80 000	30 800
"	"	81 090	"	27 200	60 000	27 200
"	"	81 497	"	29 100	60 000	29 100
"	"	107 342	"	39 500	100 000	39 500
"	"	90 418	"	31 200	80 000	31 200
"	"	80 286	"	26 200	60 000	26 200
"	"	75 883	"	27 600	50 000	27 600
"	"	87 257	"	26 700	60 000	26 700
"	"	104 716	"	39 500	100 000	39 500
"	"	80 963	"	28 200	60 000	28 200
"	"	88 848	"	32 300	80 000	32 300
"	"	95 991	"	30 500	80 000	30 500
"	"	112 072	"	35 900	80 000	35 900
"	"	89 296	"	32 800	80 000	32 800
"	"	87 877	"	31 000	80 000	31 000
"	"	90 809	"	30 000	80 000	30 000
"	"	91 004	"	30 500	80 000	30 500
"	"	96 718	"	31 600	100 000	31 600
"	"	95 836	"	32 000	80 000	32 000
"	"	87 904	"	32 000	80 000	32 000
"	"	95 513	"	30 800	80 000	30 800
"	"	106 236	"	40 400	100 000	40 400
"	"	97 033	"	33 500	100 000	33 500
"	"	110 743	"	41 100	100 000	41 100
"	"	112 512	"	43 400	100 000	43 400
"	"	110 531	"	40 600	100 000	40 600
"	"	88 994	"	31 300	80 000	31 300
"	"	85 921	"	31 800	80 000	31 800
"	"	70 984	"	23 300	40 000	23 300
Caboose	"	98 068	"			34 000

TABLE 28 Tonnage Record

Test No. S-1070

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Box	L	10 826	I. C.	31 300	60 000	96 800
"	"	131 644	"	39 600	80 000	127 100
"	E	25 703	V. S, & P.	32 000	60 000	32 000
"	L	7 628	I. C.	27 200	50 000	91 000
"	"	12 951	"	29 700		99 800
"	"	33 524	"	36 500	80 000	120 100
"	"	22 113	"	40 200	80 000	93 900
Gondola	"	97 293	"	31 500	100 000	78 500
"	"	96 803	"	34 400	100 000	74 900
Stock	E	151 427	"		40 000	29 300
"	"	150 457	"		40 000	28 100
"	"	32 589	"	31 200	60 000	31 200
"	"	32 738	"	31 000	60 000	31 000
"	"	150 986	"	30 000	40 000	30 000
"	"	4 206	S. W. S. C. L.	29 300	40 000	29 300
"	"	32 714	I C.	33 200	60 000	33 200
"	"	151 275	"	29 600	40 000	29 800
"	"	32 663	"	32 600	60 000	32 600
"	"	31 168	"	29 000	50 000	29 700
"	"	150 874	"	32 800	60 000	32 600
"	"	32 176	"	32 800	60 000	32 800
"	"	151 497	"	31 100	40 000	31 100
"	"	151 023	"	30 300	40 000	30 300
"	"	32 411	"	35 000	60 000	35 000
Box	L	142 729	"	42 900	100 000	65 200
"	"	39 777	"	37 400	80 000	61 100
"	"	19 989	"	28 300	60 000	60 900
"	E	95 571	L. & N.	34 500	65 000	34 500
"	L	140 687	I. C.	42 700	100 000	137 600
"	"	45 487	"	38 400	80 000	119 600
"	"	142 979	"	42 800	100 000	136 900
"	"	142 275	"	42 700	100 000	135 000
"	E	30 047	T. R. E.	34 800	50 000	34 800
"	"	31 974	"	32 100	50 000	32 100
Gondola	"	95 202	I. C.	30 400	80 000	31 400
"	"	96 724	"	32 000	100 000	32 000
"	"	106 393	"	40 400	100 000	40 400
"	"	87 275	"	32 200	80 000	33 200
Box	L	15 680	"	29 900	60 000	91 200
Gondola	E	96 130	"	32 000	80 000	32 000
Box	"	55 803	"	37 700	60 000	37 700
"	"	21 244	F. G. E.	36 500	50 000	36 500
Gondola	"	82 606	I. C.	27 500	60 000	27 500
"	"	82 709	"	28 800	60 000	28 800
Box	L	135 028	S.	33 700	60 000	68 700
Gondola	E	88 465	I. C.	32 600	80 000	32 600
"	"	91 623	"	30 700	80 000	30 700
"	"	106 662	"	40 000	100 000	40 000
"	"	86 231	"	31 700	80 000	31 700
"	"	80 430	"	26 500	60 000	26 500
"	"	93 350	"	31 300	80 000	31 300
"	"	94 475	"	31 100	80 000	31 100
"	"	93 620	"	30 400	80 000	30 400
"	"	96 757	"	31 800	100 000	31 800
"	"	89 088	"	30 200	80 000	30 200
"	"	82 367	"	26 800	60 000	26 800
"	"	94 594	"	30 300	80 000	30 300
"	"	92 570	"	31 000	80 000	31 000
"	"	115 109	"	43 000	100 000	43 000
"	"	81 261	"	29 000	60 000	29 000
"	"	84 172	"	28 400	60 000	28 400
"	"	83 919	"	28 200	60 000	28 200
"	"	714	C. C.C. & Co.	31 800	80 000	31 800
"	"	92 158	I. C.	30 400	80 000	30 400
Caboose	"	98 130	"			34 000

TABLE 29 TONNAGE RECORD

Test No. S-1072

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Gondola	L	106 825	I. C.	40 400	100 000	134 700
''	''	104 661	''	40 300	100 000	146 700
''	''	106 529	''	40 200	100 000	144 900
''	''	104 968	''	39 200	100 000	144 700
''	''	115 250	''	42 700	100 000	141 900
''	''	111 111	''	40 900	100 000	148 300
''	''	89 762	''	31 600	80 000	114 200
''	''	110 559	''	40 800	100 000	147 600
''	''	86 636	''	31 200	80 000	114 100
''	''	107 020	''	39 800	100 000	144 300
''	''	91 917	''	30 800	80 000	114 000
''	''	87 078	''	31 800	80 000	117 900
''	''	110 980	''	41 600	100 000	144 000
''	''	110 318	''	40 900	100 000	137 800
''	''	106 382	''	40 400	100 000	136 900
''	''	107 436	''	39 700	100 000	147 600
''	''	91 606	''	30 400	80 000	114 100
''	''	101 156	''			159 100
''	''	101 075	''		100 000	120 100
''	''	106 878	''	40 200	100 000	144 900
''	''	102 054	''	38 000	80 000	117 000
''	''	110 951	''	41 800	100 000	131 000
''	''	105 669	''	40 200	100 000	139 200
''	''	3 345	I. S.	40 100	100 000	147 700
''	''	105 713	I. C.	39 800	100 000	143 900
''	''	106 629	''	40 300	100 000	142 100
''	''	106 121	''	40 400	100 000	144 100
Caboose	E	98 155	''			35 100

TABLE 30 TONNAGE RECORD

Test No. S-1073

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Gondola	L	104 181	I. C.	40 800	100 000	139 300
''	''	110 059	''	42 300	100 000	135 800
''	''	110 679	''	42 000	100 000	135 700
''	''	111 062	''	41 000	100 000	134 500
''	''	111 336	''	40 100	100 000	134 300
''	''	112 464	''	43 400	100 000	118 600
''	''	112 431	''	43 300	100 000	118 700
''	''	106 038	''	38 800	100 000	133 700
''	''	107 581	''	40 100	100 000	130 200
''	''	3 012	I. S.	40 100	100 000	145 200
''	''	115 335	I. C.	43 000	100 000	141 600
''	''	106 459	''	40 000	100 000	138 800
''	''	3 400	I. S.	40 400	100 000	141 700
''	''	106 818	I. C.	40 500	100 000	141 200
''	''	106 087	''	41 200	100 000	141 900
''	''	3 131	I. S.	40 200	100 000	141 400
''	''	104 817	I. C.	40 400	100 000	141 800
''	''	107 217	''	39 700	100 000	141 300
''	''	107 599	''	39 600	100 000	142 000
''	''	106 101	''	40 300	100 000	141 900
''	''	106 598	''	40 200	100 000	142 500
''	''	106 197	''	40 400	100 000	138 600
''	''	104 390	''	40 700	100 000	140 400
''	''	105 651	''	40 300	100 000	140 600
''	''	106 551	''	40 000	100 000	143 100
''	''	107 124	''	39 600	100 000	140 500
''	''	106 722	''	40 300	100 000	141 300
Caboose	E		''			34 000

TABLE 31 TONNAGE RECORD

Test No. S-1074

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Gondola	"	92 451	I. C.	30 100	80 000	30 500
"	"	93 288	"	30 800	80 000	31 500
"	"	705	C. C. C. & Co.	31 300	80 000	31 200
"	"	91 779	I. C.	29 900	80 000	29 400
"	"	83 029	"	28 000	60 000	27 400
"	"	86 841	"	31 000	80 000	31 300
"	"	267	St. L. B. & S.	25 700	60 000	24 600
"	"	83 597	I. C.	27 100	60 000	27 200
"	"	82 261	"	28 300	60 000	27 700
"	"	86 473	"	31 400	80 000	31 000
"	"	94 563	"	30 600	80 000	30 700
"	"	85 327	"	30 400	80 000	32 000
"	"	92 664	"	31 200	80 000	30 500
"	"	87 201	"	32 000	80 000	32 000
"	"	95 260	"	29 800	80 000	29 400
"	"	105 612	"	40 400	100 000	40 400
"	"	93 048	"	31 500	80 000	31 200
"	"	295	St. L. B. & S.	24 000	60 000	24 500
"	"	82 249	I. C.	27 000	60 000	27 000
"	"	86 327	"	30 400	80 000	30 600
"	"	85 482	"	31 500	80 000	31 000
"	"	80 882	"	27 600	60 000	27 600
"	"	106 064	"	40 300	100 000	40 400
"	"	105 883	"	40 400	100 000	40 800
"	"	86 779	"	31 000	80 000	33 900
"	"	93 956	"	30 100	80 000	30 400
"	"	104 389	"	40 800	100 000	40 400
"	"	86 183	"	31 000	80 000	30 700
"	"	81 190	"	27 200	60 000	26 800
"	"	86 470	"	30 600	80 000	30 200
"	"	95 912	"	32 000	80 000	30 800
"	"	91 788	"	30 500	80 000	30 300
"	"	86 132	"	29 500	80 000	30 700
"	"	95 167	"	30 500	80 000	31 500
"	"	107 604	"	39 600	100 000	40 000
"	"	87 657	"	32 000	80 000	32 300
"	"	87 590	"	32 300	80 000	35 200
"	"	89 683	"	31 400	80 000	31 200
"	"	7 555	"	23 400	50 000	22 200
"	"	107 148	"	39 800	100 000	40 300
"	"	104 379	"	40 400	100 000	40 400
"	"	88 351	"	31 500	80 000	31 600
"	"	87 468	"	31 900	80 000	31 500
"	"	101 229	"	38 400	100 000	37 800
"	"	88 120	"	32 000	80 000	31 600
"	"	94 806	"	31 500	80 000	31 500
"	"	95 480	"	31 900	80 000	32 000
"	"	87 780	"	32 100	80 000	31 600
"	"	93 494	"	29 700	80 000	30 000
"	"	90 671	"	30 800	80 000	30 800
"	"	106 167	"	40 300	100 000	40 100
"	"	89 097	"	32 000	80 000	31 600
"	"	96 072	"	31 800	80 000	31 200
"	"	88 686	"	31 500	80 000	31 700
"	"	94 133	"	31 900	80 000	30 600
"	"	93 394	"	30 600	80 000	31 300
"	"	106 088	"	40 400	100 000	40 200
"	"	89 272	"	30 600	80 000	30 800
"	"	94 599	"	30 800	80 000	30 800
"	"	87 595	"	32 100	80 000	31 500
"	"	91 986	"	30 500	80 000	30 000
"	"	92 035	"	31 300	80 000	31 200

TABLE 31 TONNAGE RECORD (*Continued*)

Test No. S-1076

Kind of Car	Loaded or Empty	Car No.	Ca Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Gondola	E	93 848	I. C.	29 500	80 000	29 700
"	"	106 911	"	40 200	100 000	40 200
"	"	105 727	"	40 400	100 000	40 900
"	"	80 466	"	26 700	60 000	26 100
"	"	110 363	"	41 500	100 000	40 800
"	"	80 324	"	25 600	60 000	30 300
"	"	95 278	"	31 000	80 000	30 000
"	"	82 246	"	28 500	60 000	28 200
"	"	106 288	"	39 800	100 000	40 000
"	"	105 836	"	40 300	100 000	40 200
"	"	104 811	"	40 300	100 000	40 200
"	"	3 207	I. S.	40 300	100 000	39 800
"	"	91 420	I. C.	29 200	80 000	29 600
"	"	112 413	"	43 400	100 000	43 200
"	"	90 452	"	29 600	80 000	31 600
"	"	104 047	"	40 800	100 000	40 400
"	"	115 181	"	41 800	100 000	42 300
Caboose	"	98 005	"			32 000

TABLE 32 TONNAGE RECORD

Test No. S-1076

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Gondola	L	104 098	I. C.	41 000	100 000	149 000
"	"	104 679	"	39 200	100 000	146 000
"	"	105 091	"	40 400	100 000	148 600
"	"	105 690	"	40 300	100 000	143 400
"	"	3 344	I. S.	40 000	100 000	143 300
"	"	110 982	I. C.	41 100	100 000	137 000
"	"	104 698	"	40 600	100 000	138 500
"	"	104 023	"	40 600	100 000	142 500
"	"	107 109	"	39 700	100 000	144 000
"	"	104 361	"	40 200	100 000	148 000
"	"	107 310	"	39 700	100 000	146 000
"	"	106 268	"	40 300	100 000	147 000
"	"	104 087	"	40 900	100 000	152 000
"	"	106 161	"	40 600	100 000	146 500
"	"	107 133	"	39 700	100 000	144 900
"	"	106 144	"	40 400	100 000	150 000
"	"	111 280	"	41 600	100 000	139 000
"	"	111 229	"	40 800	100 000	135 300
"	"	110 525	"	41 300	100 000	139 300
"	"	106 713	"	40 500	100 000	143 300
"	"	110 736	"	40 700	100 000	142 000
"	"	110 421	"	43 500	100 000	148 000
"	"	110 843	"	41 200	100 000	142 400
"	"	111 061	"	41 200	100 000	141 000
"	"	107 126	"	39 700	100 000	143 000
Caboose	E	98 320	"			36 100

TABLE 33 TONNAGE RECORD

Test No. S-1077

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Test	E	17				58 000
Gondola	L	2 186	L. E. A. & W.	36 200	80 000	120 200
"	"	107 315	I. C.	39 700	100 000	138 800
"	"	106 426	"	40 500	100 000	151 800
"	"	104 103	"	37 600	100 000	153 600
"	"	88 740	"	32 000	80 000	104 600
Box	"	82 474	B. & O.	33 600	60 000	83 600
"	E	33 880	S. P.	42 700	100 000	41 900
"	"	11 238	H. & T. C.	40 200	100 000	42 800
"	L	11 150	D. S. S. & A.	32 400	60 000	73 600
"	E	10 846	N. C. & St. L.	35 400	60 000	35 000
"	E	337	G. & F.	32 500	60 000	31 700
"	"	34 552	I. C.	37 700	80 000	37 000
"	"	140 487	"	41 900	100 000	42 000
"	"	142 394	"	42 900	100 000	42 000
"	"	49 498	"	34 400	80 000	34 500
"	"	131 662	"	39 500	80 000	40 000
"	"	38 755	"	36 600	80 000	36 600
"	"	15 853	N. O. &. N. E.	30 600	60 000	30 600
"	"	9 644	L. & N.	40 800	60 000	40 700
"	"	11 712	"	30 900	60 000	30 700
"	L	15 492	I. C.	30 200	60 000	90 000
"	"	141 573	"	43 500	100 000	63 800
"	"	140 563	"	42 200	100 000	64 500
"	E	10 381	L. & N.	29 800	60 000	29 800
"	"	11 364	S.P.L.A.&S.L	43 500	100 000	43 100
"	"	11 893	N. C. & St. L.	33 400	60 000	33 300
"	"	65 969	S. P.	29 600	60 000	30 300
"	"	93 651	L. & N.	36 500	65 000	35 200
"	"	91 824	"	34 800	65 000	34 000
"	"	13 705	"	30 700	60 000	30 700
"	"	9 312	N. C. & St. L.	32 550	60 000	32 700
"	L	98 561	N. Y. C.& H.R.	35 700	80 000	78 200
"	E	12 887	C. N. O. & T. P.	34 500	60 000	33 400
"	"	4 886	N. & S.	33 600	60 000	32 000
"	"	12 027	N. & M.	37 000	80 000	30 200
"	L	131 675	I. C.	38 900	80 000	110 400
"	"	14 554	"	32 000	60 000	75 500
"	"	10 060	"	31 000	60 000	70 000
"	"	12 724	"	29 300	60 000	76 500
"	"	13 276	St. L. S. W.	32 000	60 000	79 900
"	"	26 615	I. C.	35 800	80 000	90 800
"	"	141 284	"	43 500	00 000	105 900
Gondola	E	618	E. F. D. & Co.	24 200		24 800
"	"	744	C. C. & Co.	31 800	80 000	30 600
"	"	106 729	I. C.	40 400	100 000	40 100
"	"	94 563	"	30 600	80 000	35 800
"	"	112 570	"	43 500	100 000	43 100
"	"	112 153	"	37 200	80 000	39 500
"	"	107 346	"	39 700	100 000	39 900
"	"	105 529	"	40 200	100 000	40 600
"	"	104 361	"	40 200	100 000	40 600
Caboose	"	98 370	"			35 900

TABLE 34 TONNAGE RECORD

Test No. S-1079

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Box	E	11 050	H. & T. C.	42 100	100 000	36 200
"	"	43 031	M. C.	30 700	60 000	30 400
"	"	41 654	C. & N. W.	27 100	40 000	27 700
"	L	31 135	C. R. I. & P.	36 300	80 000	80 800
"	"	15 746	I. C.	29 600	60 000	69 000
"	"	22 691	S. P.	26 600	50 000	70 000
Refrigerator	E	6 696	A. R. L.	35 600	50 000	34 000
Box	L	14 053	I. C.	30 500	60 000	70 400
"	"	33 125	"	36 200	80 000	89 600
"	"	39 747	"	36 200	80 000	72 500
"	"	46 477	"	37 200	80 000	76 000
"	"	30 352	R. I. A. & L.	36 400	80 000	74 000
"	"	131 445	I. C.	39 800	80 000	80 000
"	"	19 385	M. P.	32 000	60 000	62 000
"	"	70 716	B. & O.	30 800	60 000	67 600
"	"	31 563	C. R. I. & P.	38 700	80 000	93 500
"	"	700	H. E. & W. T.	31 700	60 000	80 000
"	"	12 116	Mex. Cent.	30 600	27 500K	86 700
Gondola	"	87 798	I. C.	31 600	80 000	66 400
Box	"	46 057	"	39 400	80 000	80 400
"	"	12 562	"	30 300	60 000	69 600
"	"	131 611	"	39 000	80 000	63 600
"	"	142 973	"	41 000	100 000	80 000
"	"	50 174	C. & G. W.	38 400	60 000	79 000
"	"	34 506	I. C.	37 500	80 000	62 700
Gondola	"	82 347	"	27 300		85 600
Box	"	37 578	"	33 000	80 000	85 000
Refrigerator	E	6 459	M. & Co. R. L.			36 700
Gondola	L	97 161	I. C.	32 700	100 000	86 500
Box	"	14 550	"	29 800	60 000	65 300
Gondola	"	91 822	"	31 000	80 000	97 000
Box	"	15 713	"	29 900	60 000	72 500
Refrigerator	E	4 068	M. F. T. Co.	40 500	60 000	40 400
"	"	5 886	A. R. L.	31 900	50 000	34 000
Box	L	142 042	I. C.	42 900	100 000	83 000
Refrigerator	E	307	U. R. T. Co.	38 000	40 000	39 000
Box	L	131 734	I. C.	39 300	80 000	88 700
Refrigerator	E	3 831	U. R. T. Co.		40 000	36 500
Box	"	74 936	Erie	32 200	60 000	32 400
Refrigerator	"	20 018	F G. E.	38 700	50 000	33 800
"	"	6 115	A. R. L.	36 500	50 000	37 700
Box	L	85 137	U. P.	39 700	80 000	89 000
Gondola	"	111 101	I. C.	40 500	100 000	78 600
Refrigerator	E	1 840	M. R. D.	37 500	60 000	38 500
Box	L	72 907	Penn.	30 900	60 000	91 000
"	"	25 346	C. B. & Q.	27 400	60 000	70 200
"	"	60 245	S. P.	35 200	60 000	88 500
"	"	64 733	"	29 600	60 000	75 500
"	"	11 771	I. C.	29 500	60 000	65 500
"	"	13 983	K. C. S.	31 600	60 000	82 300
Caboose	E	98 260	I. C.			35 400

TABLE 35 Tonnage Record

Test No. S-1080

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Box	L	10 315	I. C.	30 400	60 000	91 200
"	"	141 744	"	43 600	100 000	147 100
"	"	141 622	"	43 600	100 000	135 200
"	"	21 385	"	36 600	80 000	124 200
"	E	31 478	T. R. E.	32 200	50 000	33 400
"	L	38 140	I. C.	34 400	80 000	125 000
"	"	48 223	"	39 800	80 000	89 300
Gondola	E	104 852	"	40 000	100 000	39 400
"	"	105 936	"	40 000	100 000	40 000
"	"	88 440	"	31 600	80 000	31 600
Box	"	12 090	M. L. & T.	32 000	60 000	31 800
Gondola	"	90 647	I. C.	31 500	80 000	31 600
"	"	82 853	"	28 400	60 000	27 900
"	"	107 665	"	39 900	100 000	39 900
"	"	106 701	"	40 600	100 000	40 400
"	"	106 321	"	40 400	100 000	40 200
"	"	3 354	I S	40 400	100 000	40 100
"	"	104 969	I C.	40 000	100 000	40 000
"	"	106 793	"	40 200	100 000	40 100
"	"	101 154	"	37 600	100 000	37 800
"	"	100 021	"	32 700	90 000	33 000
"	"	107 624	"	39 600	100 000	40 000
"	"	107 217	"	39 700	100 000	39 900
"	"	106 305	"	39 400	100 000	40 100
"	"	104 027	"	40 400	100 000	40 500
"	"	94 971	"	33 200	80 000	31 900
"	"	94 209	"	30 600	80 000	30 800
"	"	87 979	"	32 000	80 000	31 600
"	"	76 795	"	30 000	50 000	29 900
"	"	110 818	"	41 600	100 000	41 400
"	"	107 532	"	39 500	100 000	40 200
"	"	92 400	"	31 500	80 000	31 500
"	"	88 001	"	31 200	80 000	31 100
"	"	3 009	I. S.	40 300	100 000	40 300
"	"	89 391	I. C.	30 700	80 000	30 500
"	"	94 566	"	30 900	80 000	30 700
"	"	104 167	"	40 800	100 000	40 700
"	"	91 513	"	30 200	80 000	30 200
"	"	91 465	"	30 400	80 000	30 400
"	"	86 098	"	34 300	80 000	31 600
"	"	85 444	"	31 000	80 000	30 900
"	"	87 389	"	31 400	80 000	31 400
"	"	91 106	"	31 400	80 000	31 300
"	"	111 131	"	40 800	100 000	30 700
"	"	90 929	"	31 700	80 000	31 600
"	"	100 071	"	32 900	90 000	32 900
"	"	89 481	"	31 800	80 000	31 400
"	"	104 746	"	40 400	100 000	40 400
"	"	87 877	"	31 000	80 000	30 600
"	"	92 494	"	26 800	80 000	30 100
"	"	101 177	"	37 700	100 000	37 800
"	"	86 841	"	31 000	80 000	31 200
"	"	85 409	"	31 800	80 000	31 600
"	"	89 100	"	32 600	80 000	31 000
"	"	83 948	"	27 600	60 000	27 900
"	"	94 065	"	30 900	80 000	30 800
"	"	82 328	"	28 400	60 000	27 900
"	"	87 302	"	30 600	80 000	38 800
"	"	102 002	"	38 000	80 000	37 800
"	"	88 051	"	31 300	80 000	31 600
"	"	91 268	"	30 500	80 000	30 500
Caboose	"	98 413	"			34 800

APPENDIX 3

APPENDIX 3

THE TRACK

All tests, except No. S-1030A, were made over the 91 miles of Illinois Central main line track lying between Gilman (mile 81.12) and Mattoon (mile 172.38), Illinois.

Roadbed.—This track, formerly a part of one of the oldest single track lines in the State, was converted about ten years ago into a double track road; and the roadbed is now well settled and in good condition. In construction the roadbed has been made to conform as closely as practicable to the standard Illinois Central section for class A double track. This section has a 34-ft. crown with a slope of $1\frac{1}{2}$ to 1 for embankments, and a $46\frac{1}{2}$-ft. base with slopes of 1 to 1 or $1\frac{1}{2}$ to 1 for cuts. The drainage of the track is, in general, excellent.

Ballast and Ties.—Except on a few short stretches through station grounds where screenings are used for ballast, both tracks are ballasted with broken limestone throughout this distance. There is not less than 12 in. of ballast beneath the ties, and the ballast shoulder extends 12 in. beyond the ties whence it runs off to the sub grade on a slope of $1\frac{3}{4}$ to 1. The cross ties are of either untreated white oak or treated red oak, and are 6 in. by 8 in. by 8 ft. long. They are spaced about 20 in. from center to center.

Rail.—The south-bound or west track between mile 161+3500 ft. and mile 171 is laid with rail weighing 75 lb. per yard. The remainder of the west track and all of the east track are laid with rail weighing 85 lb. per yard. The 75-lb. rail is of the standard American Society of Civil Engineers' section, rolled by the Illinois Steel Company, and is further designated as Illinois Steel Company's section No. 7506. All 85-lb. rail is of standard A. S. C. E. section, and Illinois Steel Company's section No. 8504.

Rail Joints and Fastenings.—All rails are laid with square joints, supported on three ties. The 75-lb. rails are joined with Illinois Central Standard 40-in. angle-bar splices, weighing 76 lb. per pair; and the 85-lb. rails are joined with similar splices weighing 80-lb. per pair. In each joint six track bolts are used, which are $\frac{3}{4}$ by $4\frac{1}{8}$ in. for the 75-lb. rails, and $\frac{7}{8}$ by $4\frac{1}{2}$ in. for the 85-lb. rails. Four $\frac{9}{16}$ by $5\frac{1}{2}$ in. track spikes are used in each cross tie. No tie plates or rail braces are used, except through switches.

Maintenance.—During eight months of the year there is employed in maintaining this portion of the road a force of men averaging one man per mile of track; during the remaining four months this force is reduced to one man for each two miles.

APPENDIX 4

APPENDIX 4

METHODS EMPLOYED IN CALCULATING THE RESULTS

This appendix presents a detailed explanation of the processes used throughout this investigation in deriving the results of the tests. Two methods of calculation have been employed. By one method resistance was determined at a point on the road; by the other, the average resistance was determined for the period during which the test car passed over a certain track section. The former is termed Method 1, the latter, Method 2. A general statement and comparison of the two methods and an explanation of the general limitations imposed upon the selection of points and sections have been given in Part I. Whatever is said under "Methods Employed in Calculating the Results" in Part I is to be considered as supplementary to the contents of this Appendix.

THE ELEMENTS OF GROSS RESISTANCE

The various elements which make up gross train resistance are:

1. Net resistance on straight, level track, at uniform speed, in still air.
2. Resistance due to wind, (as distinguished from still air resistance).
3. Resistance due to grade.
4. Resistance due to acceleration.
5. Resistance due to track curvature.

Item 1 is always in operation to retard a moving train. One or more (or none) of the others may also be acting with item 1 to form gross resistance.

The dynamometer car records directly the gross resistance or drawbar pull as here defined. The purpose of the calculations has been to determine net resistance (item 1); or more strictly speaking, the purpose, by force of circumstances, has been to determine the sum of net resistance (item 1), and wind resistance (item 2), since it has been impossible to differentiate the latter from the other elements. Curve resistance has been entirely eliminated from consideration by selecting for calculation only those points and sections where the train was on tangent track. Grade resistance and acceleration resistance may always be determined by calculation; and in order to find the net resistance, it is necessary only to subtract these two items (3 and 4) from the gross resistance recorded on the test car chart.

Since the process employed implies the ability to calculate the grade and acceleration resistances, their determination will be explained before proceeding with the explanation of the two methods by which net resistance was derived.

The following general notation is used throughout. Other special notation needed in the development of the analysis is given as the necessity arises.

NOTATION:

P = Total gross resistance = drawbar pull.—pounds.

R = Net resistance on tangent, level track, at uniform speed.—pounds per ton.

R_g = Resistance due to grade.—pounds per ton.

R_a = Resistance due to acceleration.—pounds per ton.

W = Total train weight.—tons.

V, V_1, etc. = Train speed.—miles per hour.

G = Grade.—feet per mile.

A = Acceleration of the train speed.—miles per hour per second.

a = Acceleration of the train speed.—feet per second per second.

E_1 and E_2 = Elevations of the center of mass of the train.—feet.

S = Length of track section used in Method 2.—feet.

N = Number of cars in the train.

GRADE RESISTANCE

If the train be on a uniform grade of G feet per mile, the grade resistance in pounds per ton is at the moment:

$$R_g = 0.379 \times G \ldots\ldots\ldots\ldots\ldots\ldots (15).$$

If it be desired to find the average grade resistance during the period in which the test car passes a certain section of track, we must determine the elevations of the center of mass of the train at the moments the car enters and leaves the section. If we call these elevations E_1 and E_2 respectively, and the length of the section S (in feet), then the average grade in feet per mile is:

$$G = (E_2 - E_1) \times \frac{5280}{S}$$

and

$$R_g = 0.379 \times (E_2 - E_1) \times \frac{5280}{S} = \frac{2001\ (E_2 - E_1)}{S} \ldots\ldots (16).$$

G and $(E_2 - E_1)$ in these equations may be found directly from the profile; and S may be calculated from the profile or from the dynamometer chart. To give correct results, the entire train must be on uniform grade at the moments for which G, E_1 and E_2 are determined.

ACCELERATION RESISTANCE

The total force needed to produce acceleration is made up of two parts. The first is the force needed to produce acceleration in the motion of translation of the train as a whole; and the second is the force needed to produce acceleration in the rotation of the wheels and axles. This total force is the total acceleration resistance R_a.

Let

R_a = Acceleration resistance due to both translation and rotation. —pounds per ton.

F = Total drawbar pull needed to produce the acceleration.—pounds.

T = Drawbar pull needed to produce acceleration in the translation of the whole train.—pounds.

f = Drawbar pull needed to produce acceleration in the rotation of all wheels and axles. – pounds.

Then

$$R_a = \frac{F}{W}$$

and

$$F = T + f$$

therefore

$$R_a = \frac{T + f}{W} \ldots\ldots\ldots\ldots\ldots\ldots (17).$$

T and f in this equation are found as follows:

$$T = \text{mass} \times \text{acceleration} = \frac{W \times 2000}{32.2} \times a$$

but

$$a = A \times \frac{5280}{60 \times 60} = 1.466\ A$$

hence

$$T = \frac{W \times 2000 \times 1.466\ A}{32.2} = 91.05\ A\ W \ldots\ldots (18).$$

To find f:

Let

p = Drawbar pull required to produce the acceleration in the rotation of one pair of wheels and their axle.—pounds. This is to be considered as a force applied at the wheel rim.

p_1 = Force which, applied at the end of the "radius of gyration", would produce the acceleration in rotation produced by p.

r = Wheel radius.—any unit.

k = Radius of gyration of one pair of wheels and axle.—same unit as r.

w = Weight of one pair of wheels and their axle. — pounds.

a = Acceleration in the linear velocity of a point on the wheel rim.—feet per second per second. This equals the acceleration of the train.

b = Acceleration in the linear velocity of a point at the end of the radius of gyration.—feet per second per second.

w is taken as equal to 1950 lb[1], which is the approximate mean between the weight of a $4\frac{1}{4}$ by 8 axle and its wheels and the weight of a 5 x 9 axle and its wheels. $\frac{k}{r}$ is found to be about 0.64 for various axles and wheels[1].

Since cars have 4 axles, we have:

$$f = 4\,N \times p$$

$$p = \frac{k}{r} \times p_1$$

$$p_1 = \frac{w}{32.2} \times b = \frac{1950}{32.2} \times b = 60.56\,b$$

$$b = a\,\frac{k}{r} = 1.466\,A \times \frac{k}{r}$$

$$p_1 = 60.56 \times 1.466\,A \times \frac{k}{r} = 88.82\,A \times \frac{k}{r}$$

$$p = 88.82\,A \times \frac{k^2}{r^2} = 88.82 \times (0.64)^2 \times A = 36.38\,A,$$

and

$$f = 4 \times N \times 36.38\,A = 145.5\,A\,N \ldots\ldots\ldots\ldots\ldots\ldots (19)$$

---

[1] The maximum error in Ra which may result from possible variations in w and $\frac{k}{r}$ under current standards of car design is 1.1 per cent. Ra in the calculations seldom exceeds R. and the maximum probable error in R due to such variations is therefore about one per cent. It would occur with a train of *empty* gondolas equipped with 5½ x 10 journals and wheels weighing 725 lb. each.

From equations 17, 18, and 19

$$R_a = \frac{T}{W} + \frac{f}{W}$$

Hence

$$R_a = \left(91.05 + 145.5\,\frac{N}{W}\right) \times A \qquad (20).$$

Formula 20 may be applied to find the momentary acceleration resistance at a point on the road, or to determine its average value while the train passes a certain section. In the former case A denotes the momentary acceleration, and in the latter case A denotes the average acceleration over the section. N and W are derived from the train data. In either case A may be found as explained below.

The determination of acceleration.—In determining the net resistance by Method 1—at a point on the road—the momentary value of A in formula 20 has been determined as follows. In this discussion it should be remembered that all curves on the dynamometer chart are drawn on a distance base, i. e., to some scale their abscissas represent distances, in feet.

On the speed curve in Fig. 17, let B represent the point on the road which is under consideration. At B draw the tangent $O\ D$ to this curve, and select on this tangent the points C and D *equidistant* from B. This tangent may be considered as a speed curve which at B represents the same acceleration as the actual speed curve. By direct measurement the ordinates of the tangent at C and D are determined as v_1 and v_2, respectively. Similarly the distance S may be determined. The speed at B is called v. The acceleration A at the point B is then determined thus:

Let

v, v_1, v_2 = Speed.—feet per second.

V_1, V_2 = Speed.—miles per hour.

t = Time.—seconds.

l = Distance.—feet.

a = Acceleration.— feet per second per second.

Then

$$a = \frac{d\,v}{d\,t}$$

and

$$d\,t = \frac{d\,l}{v}$$

hence

$$a = \frac{vdv}{dl}$$

The equation of the tangent referred to the axes Ov and Ol is:

$$v = ml$$

$$m = \frac{v_2 - v_1}{S}$$

$$v = \frac{v_2 - v_1}{S} \times l$$

whence

$$d\,v = \frac{v_2 - v_1}{S}\,d\,l$$

and

$$\frac{d\,v}{dl} = \frac{v_2 - v_1}{S}$$

also, since v is the mean between v_1 and v_2,

$$v = \frac{v_2 + v_1}{2}$$

therefore

$$a = \frac{vdv}{d\,l} = \frac{v_2 + v_1}{2} \times \frac{v_2 - v_1}{S} = \frac{v_2^2 - v_1^2}{2\,S}$$

but

$$a = 1.466\,A$$

and

$$v = 1.466\,V,$$

hence

$$A = \frac{(1.466)^2 \times (V_2^2 - V_1^2)}{1.466 \times 2\,S} = 0.733\frac{V_2^2 - V_1^2}{S} \quad \text{.............(21).}$$

Formula 21 is used to determine the momentary acceleration at a point B on the speed curve. V_1 and V_2 are ordinates at the two points, C and D, located on the tangent drawn at B and equidistant from B. To draw this tangent with sufficient accuracy, the speed curve must be nearly a straight line for a small distance on either side of B.

In determining the net resistance by Method 2—while the test car passes a certain track section—the average value of A in formula 20 has been determined as follows. The conditions are represented in Fig. 18.

Let a = the *uniform* acceleration which, acting during the passage of the car through the section, would have caused a speed change the same as that actually produced.—feet per second per second.

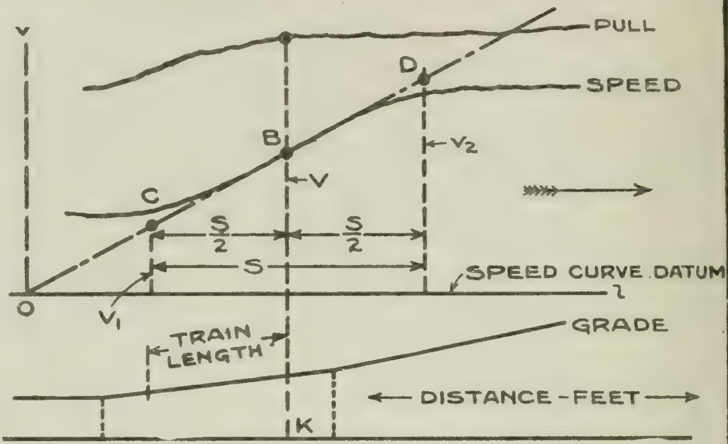

FIGURE 17

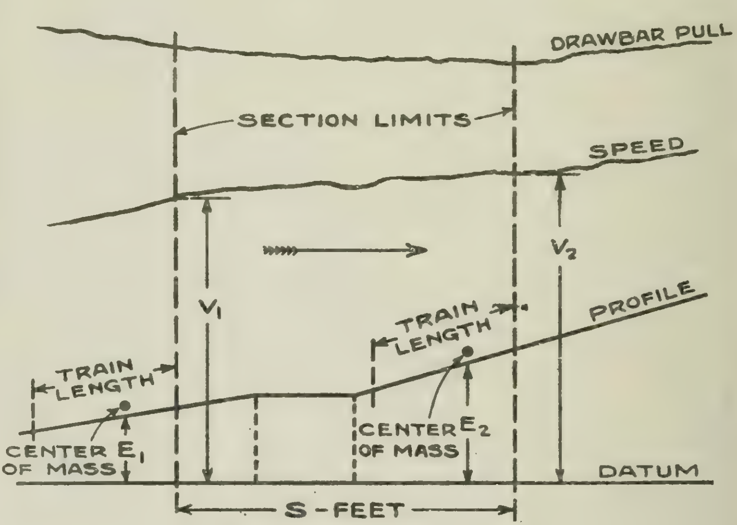

FIGURE 18

FIG. 17 DIAGRAM USED IN THE EXPLANATION OF METHOD I
FIG. 18. DIAGRAM USED IN THE EXPLANATION OF METHOD II

A = The same, expressed in miles per hour per second.
v_1 and v_2 = Speeds at entrance and exit.—feet per second.
V_1 and V_2 = Speeds at entrance and exit.—miles per hour.
S = The length of the section.—feet.
t = The time elapsed in transit over the section.—seconds.

Then

$$v_2 = v_1 + a\,t$$

and

$$S = v_1 t + \frac{a\,t^2}{2}$$

whence, by the elimination of t,

$$a = \frac{v_2^2 - v_1^2}{2\,S}$$

and, since

$$a = 1.466\,A$$

and

$$v = 1.466\,V,$$

$$A = 0.733\,\frac{V_2^2 - V_1^2}{S} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (22)$$

This equation is identical in form with equation 21. It is used to determine the average acceleration over a given track section. In it A is to be understood as that hypothetical uniform acceleration which, acting during transit over the section, would have caused the absorption of the same energy as was actually expended to produce acceleration under the prevailing speed changes. V_1 is the speed at the moment the head of the train enters the section. V_2 is the speed at the moment the head of the train leaves the section. S is the length of the section.

Formula 22 is correct for all cases, regardless of the shape or variations of the speed curve. However, for reasons which are entirely unrelated to the accuracy of the acceleration determination and which have been explained in Part I, the sections were so chosen that V_1 and V_2 varied but slightly, and that the speed curve between the section limits presented no great speed variations.

THE DETERMINATION OF NET RESISTANCE

Net resistance on straight, level track, at uniform speed is termed R, and is expressed in pounds per ton. In both methods of calculation its value was derived from the equation:

$$R = \frac{P}{W} - R_g - R_a \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (23).$$

In which P is determined from the test car chart, W from train data, and R_g and R_a as previously explained.

Method No. 1.—To determine R at a point on the track, equations 23, 15, and 20 may be used; these when combined give us:

$$R = \frac{P}{W} - 0.379G - (91.05 + 145.5 \frac{N}{W}) \times A \ldots\ldots\ldots\ldots (24).$$

If the train is on a down grade the sign of the second term should be changed to plus. The value of A should be found by means of equation 21, and, as there explained, by drawing a tangent to the speed curve. The other quantities in the equation,—W, N, P, S, and G, may be found directly from the train data, or the dynamometer chart, or the profile. Fig. 17 represents the conditions which prevailed at points chosen for the calculations by this method. In Fig. 17 the line KB represents the point on the road which is under consideration. All values of momentary resistance included in this report have been found by means of formula 24.

In the selection of points for the application of Method 1, the following precautions must be and have been observed:

1. The entire train must be on tangent track and on a uniform grade.
2. The speed curve must be nearly straight for a certain distance either side of the point chosen, in order to permit the tangent to be accurately drawn.
3. The acceleration should preferably be low. The maximum acceleration at any point chosen for the calculation of values included in this report was 0.106 miles per hour per second.

Method No. 2. To determine the mean value of R over a certain track section, equations 23, 16, and 20 may be used; these when combined give:

$$R = \frac{P}{W} - \frac{2001 \times (E_2 - E_1)}{S} - (91.05 + 145.5 \frac{N}{W}) \times A \ldots\ldots (25).$$

In this case the value of A should be found by means of equation 22. The quantities to be determined in order to use formula 25 are W, N, P, S, V_1, V_2 and $(E_2 - E_1)$. W and N are derived from the train data. P is the mean drawbar pull over the section, and is found by determining by the use of a planimeter the mean height of the pull curve between the section limits. S is the section length and may be found directly from the dynamometer chart. V_1 is the speed as the train enters the section. V_2 is the speed as the train leaves the section. V_1 and V_2 are determined directly from the dynamometer chart. E_1 is the elevation of the center of mass of the train at the moment its head end enters the section. E_2 is the corresponding elevation at the moment the head end of the train leaves the section. The quantity $(E_2 - E_1)$ is found from the profile. R in this case corresponds to the mean speed over the section. This mean speed is determined by means of the records of time and distance. Fig. 18 represents the conditions which prevailed at sections chosen for the calculations by this method. In Fig. 15, Appendix 1, is represented the section from which the results for item 12 of test S-1057 were derived. All values of mean resistance included in this report have been found by formula 25.

In the selection of points for the application of Method 2, the following precautions must be and have been observed:

1. The track must be straight over the section and also for a distance (equal to the train length) before the entrance to the section.
2. The entire train must be on a uniform grade at the moment its head end enters the section, and again at the moment it leaves the section. These grades need not, however, be alike.
3. For reasons which have been explained in Part I, the speed curve between the section limits should not present great speed variations nor should the difference between V_1 and V_2 be greater than ten or twelve miles per hour.

APPENDIX 5

APPENDIX 5

THE RESULTS OF THE INDIVIDUAL TESTS

Appendix 5 exhibits for each test a table showing the main results of the calculations. Where both methods of calculation have been employed, the tables show two groups of items. The one group displays the results obtained by Method 1, and the other shows those obtained by Method 2. The notation following the column headings is the same as that used in Appendix 4. The final values of net resistance on tangent, level track, at uniform speed are given in column 13, and the corresponding values of speed are given in column 12.

Following the table of results for each test is a figure which shows the relation between speed and resistance for the same test. The coordinates of the points plotted in these diagrams are the values of speed and resistance given in columns 12 and 13 of the corresponding table. The points represented in the diagrams by circles are plotted from values of momentary speed and momentary resistance obtained by Method 1. The points represented by circular black spots are plotted from values of average speed and average resistance obtained by Method 2. The numbers shown at the points are the corresponding item numbers given in column 2 in the table.

The curves represent for each test the mean relation between resistance and speed. In order to draw these curves, the plotted points were assumed to be arranged in a number of groups for each of which the "center of gravity" was determined and plotted on the diagram. The curve was then drawn by confining attention to the few points thus determined. The groups of points were arbitrarily selected so that the resulting "centers of gravity" were almost equidistantly distributed throughout the speed range.

TABLE 36 TEST NO. S-1013

From Champaign to Gilman, April 27, 1908. Weather: Intermittent rain. Temperature: 42° F. at start, 44° F. at end of test. Total weight behind measuring drawbar = 2549 tons, including the test car. Train length = 2784 ft. Center of mass 1425 ft. back of measuring drawbar. 67 cars: 10 empty, 57 loaded. Kind of cars: 53 box, 9 gondola, 3 tank, 1 test, 1 caboose. Average weight per car = 38.04 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
						Speeds			Wind			
Method of Calculation	Item No.	Location on Road Milepost No.	Length of Section feet	Total Drawbar Pull pounds	Acceleration miles per hour per second	At Entrance to Section m. p. h.	At Exit from Section m. p. h.	Grade + Up — Down feet per mile	Approximate Direction	Approximate Velocity m. p. h.	Speed m. p. h.	Net Train Resistance pounds per ton
				P	A	V_1	V_2	G			V	R
Point Columns 5, 6, and 9 to 13 show Momentary Values	2	116.67		16400	0			+1.48	+50° L	18	18.20	5.86
	3	112.23		13750	0			—2.78	90° L	19	24.30	6.45
	4	110.46		29600	0			+16.50	90° L	19	11.50	5.34
	5	108.80		11900	0			—4.82	+40° L	25	24.60	6.50
	7	105.86		9850	0			—10.00	+50° L	22	32.70	7.65
	8	100.51		23000	0			+8.52	+90° L	17	12.70	5.79
	9	99.29		12750	0			—5.74	+35° L	21	27.50	7.18
	10	91.00		12500	0			—2.59	+55° L	15	26.30	5.89
	11	90.08		12550	+0.0280			—9.32	+55° L	27	27.50	5.81
	12	87.00		13100	0			—2.23	+45° L	17	24.10	5.99
	13	86.15		15300	0			0.00	90° L	17	20.70	6.00
	14	84.46		16400	—0.0200			+6.20	90° L	14	18.40	6.00
	15	83.24		12250	0			—5.00	90° L	21	25.10	6.71
	16	81.86		13000	0			—1.67	90° L	15	16.00	5.73
Section Columns 5, 6, and 9 to 13 show Average Values	4	116.25—117.00	3960	16400		18.20	18.20	+2.00	+50° L	18	18.20	5.68
	5	110.46—111.00	2870	30000		11.60	11.60	+19.32	+90° L	19	11.60	4.45
	6	100.82—101.55	3880	23700		12.60	12.60	+10.60	+90° L	17	12.60	5.29

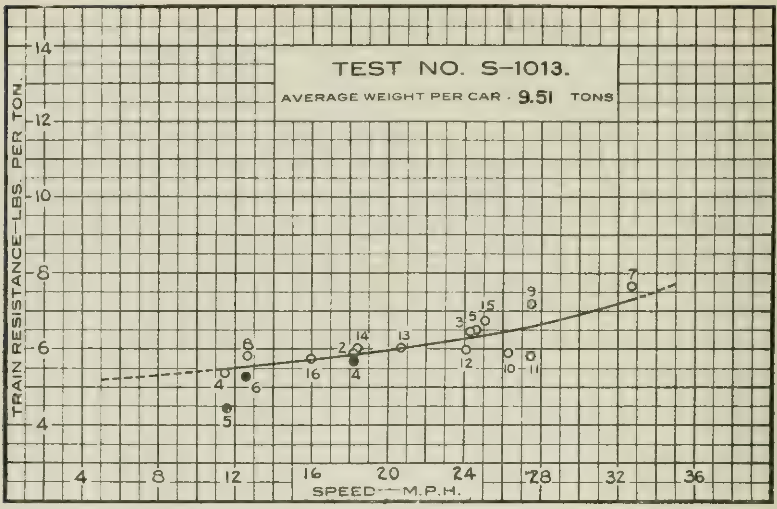

FIG. 19 TO 50 CURVES SHOWING THE RELATION BETWEEN RESISTANCE AND SPEED FOR EACH OF THE 32 TESTS

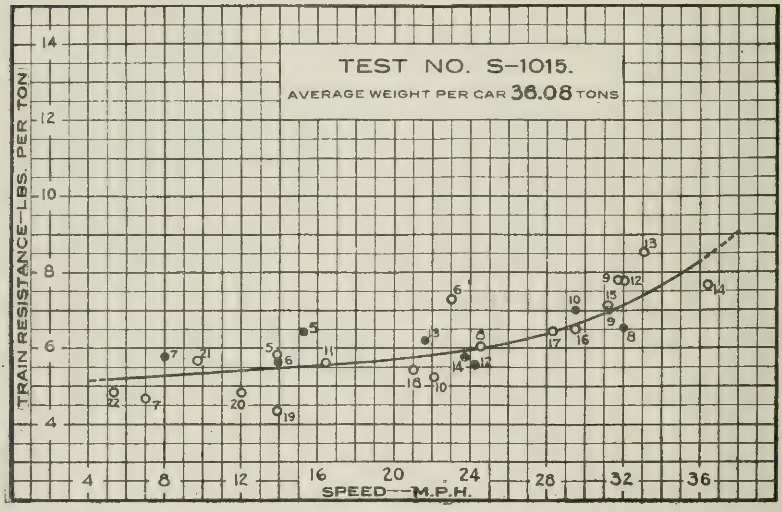

FIG. 20

TABLE 37 TEST NO. S-1015*

From Champaign to Gilman, April 29, 1908. Weather: Fair. Temperature: 40° F. at start, 48° F. at end of test. Total weight behind measuring drawbar = 2489 tons, excluding the test car. Train length = 2520 ft. Center of mass 1200 ft. back of measuring drawbar. 69 cars: 8 empty, 61 loaded. Kind of cars: 46 box, 4 gondola, 11 flat, 7 tank, 1 caboose. Average weight per car = 36.08 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 Show Momentary Values	5	114.35		21800	0			+ 7.96	+80°L	6	13.90	5.84
	6	112.27		14800	0			− 3.56	+50°L	10	23.00	7.30
	7	110.64		31000	0			+20.50	+65°L	7	7.00	4.68
	8	108.67		13900	−0.0220			+ 4.39	+60°L	9	24.50	6.02
	9	105.95		10500	+0.0220			−15.04	+40°L	15	31.77	7.80
	10	101.76		11600	0			− 1.47	+30°L	12	22.10	5.23
	11	100.49		18500	0			+ 4.82	+55°L	6	16.40	5.61
	12	96.91		3750	0			−16.55	+35°L	15	32.10	7.79
	13	96.00		5500	+0.0621			−27.00	+45°L	15	33.10	8.51
	14	95.48		3500	+0.0300			−24.00	+55°L	11	36.40	7.65
	15	94.00		5250	0			13.20	+30°L	16	31.25	7.11
	16	92.00		5500	0			−11.30	+60°L	7	29.50	6.50
	17	90.00		7750	0			− 8.80	+80°L	12	28.25	6.44
	18	86.00		12500	0			− 1.05	−80°L	10	21.00	5.42
	19	103.44		25800	−0.0587			+30.60	+35°L	10	13.90	4.35
	20	103.35		28000	−0.0587			+31.60	+25°L	8	12.00	4.84
	21	103.25		31600	−0.0587			+33.00	+25°L	6	9.70	5.69
	22	103.02		36750	−0.0140			+29.70	+65°L	2	5.28	4.85
Section Columns 5, 6, and 9 to 13 show Average Values	6	114.81 – 114.18	3310	22200		13.90	13.90	+ 8.62	+80°L	6	13.90	5.66
	7	111.22 – 110.58	3380	31500		9.00	7.00	+19.82	+65°L	7	8.00	5.80
	8	97.16 – 96.19	5160	5250		31.40	31.70	−12.38	+55°L	11	32.00	6.51
	9	94.18 – 93.54	3120	5250		31.20	31.20	−12.96	+30°L	16	31.20	7.03
	12	88.14 – 87.12	5380	10000		24.20	24.20	− 4.12	+40°L	10	24.20	5.58
	13	86.31 – 85.44	4650	12500		21.50	21.70	− 3.52	−80°L	10	21.60	6.21
	14	83.80 – 82.79	5380	11200		22.80	24.70	6.48	+80°L	12	23.70	5.79

* For complete table heading see Table 36, p. 99.

TABLE 38 TEST NO. S-1016*

From Gilman to Champaign, April 30, 1908. Weather: Fair. Temperature: 44° F. at start, 48° F. at end of test. Total weight behind measuring drawbar = 1161 tons, including the test car. Train length = 3030 ft. Center of mass 1515 ft. back of measuring drawbar. 72 cars: 72 empty, 0 loaded. Kind of cars: 70 gondolas, 1 test, 1 caboose. Average weight per car = 16 12 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed A	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	9	94.57		14400	0			+12.21	+55°R	14	11.20	7.77
	10	95.55		10450	0			+ 5.06	+60°R	10	16.30	7.08
	11	96.61		20250	0			+25.80	+55°R	10	9.50	7.66
	12	98.67		21500	0			+28.80	+55°R	6	8.30	7.60
	15	105.66		6250	—0.0118			— 8.20	+30°R	12	24.10	9.74
	16	106.27		9250	—0.0300			— 4.44	+35°R	11	22.90	9.28
	17	106.91		13600	—0.0117			+13.25	+35°R	7	17.10	7.85
	18	107.39		14750	—0.0117			+17.40	+30°R	10	16.60	7.27
	19	107.75		14700	—0.0117			+16.20	+25°R	9	15.00	7.67
	21	115.89		7500	0			— 7.32	+20°R	9	23.60	9.23
	22	117.65		8000	0			— 1.57	+20°R	9	21.30	7.48
	23	109.22		9900	0			— 1.92	+30°R	11	20.10	9.26
	24	99.70		8750	0			— 4.87	+20°R	15	18.90	9.38
Section Columns 5, 6, and 9 to 13 show Average Values	5	98.23— 98.85	3280	21000		9.25	7.40	+29.90	+55°R	6	8.75	7.43
	6	104.37—104.88	2675	6000		25.00	25.00	—16.78	+40°R	10	25.00	11.52
	7	105.17—105.66	2596	6200		25.65	24.53	—11.30	+40°R	11	25.30	11.15
	8	105.66—106.27	3208	8400		24.28	22.90	— 3.62	+30°R	12	24.00	10.10
	9	106.91—107.37	2430	14000		18.20	16.60	+14.13	+35°R	7	17.40	7.56
	10	107.37—107.75	2030	14300		16.60	14.90	+16.65	+30°R	10	15.70	7.96
	11	115.65—116.15	2640	7400		23.30	23.30	— 6.40	+20°R	9	23.40	8.79
	12	116.68—117.65	5120	7750		22.50	21.40	— 2.68	+20°R	9	21.95	7.77
	13	118.17—120.37	11570	10250		22.00	23.30	— 0.14	+15°R	11	22.65	8.51
	14	120.33—121.64	6950	10000		23.30	24.20	— 2.58	+35°R	8	23.75	9.13
	15	123.20—125.07	9880	10200		22.30	22.30	— 0.27	+35°R	9	22.30	8.90
	16	111.45—111.79	1752	6600		24.16	26.15	—22.90			25.15	10.18
	17	111.79—112.28	2604	6500		26.15	29.10	—29.65			27.65	12.26
	18	112.28—112.62	600	3500		29.17	29.42	—28.20			29.20	11.87

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* For complete table heading see Table 36. p. 99.

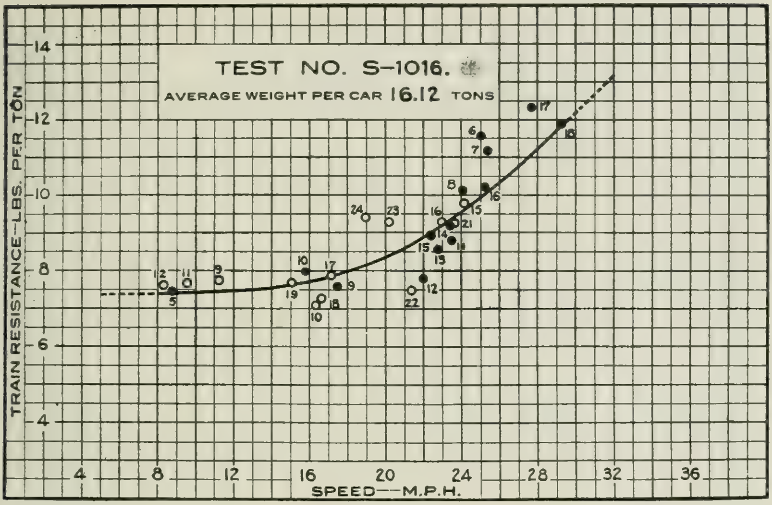
TEST NO. S-1016.
AVERAGE WEIGHT PER CAR 16.12 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
4
6
8
10
12
14
4
8
12
16
20
24
28
32
36

Fig. 21

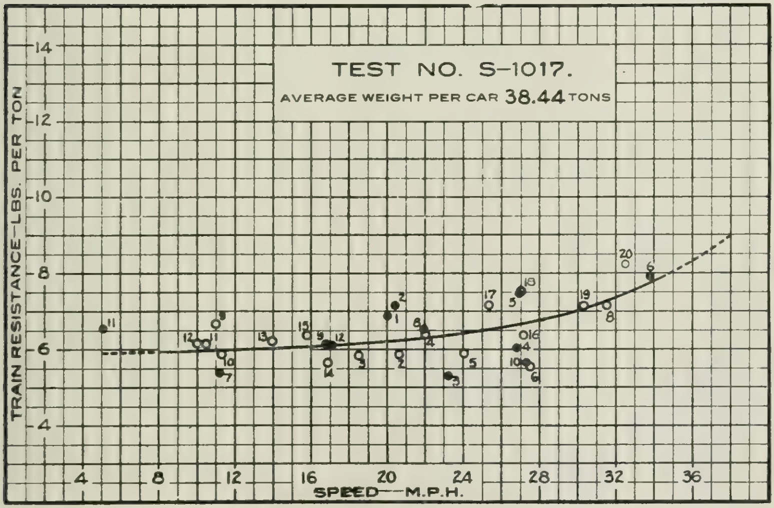
TEST NO. S-1017.
AVERAGE WEIGHT PER CAR 38.44 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
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Fig. 22

TABLE 39 TEST NO. S-1017*

From Champaign to Gilman, May 1, 1908. Weather: Intermittent rain. Temperature: 48° F. at start, 54° F. at end of test. Total weight behind measuring drawbar = 2532 tons, excluding the test car. Train length = 2670 ft. Center of mass 1200 ft. back of measuring drawbar. 66 cars: 13 empty, 53 loaded. Kind of cars: 62 box, 3 gondola, 1 caboose. Average weight per car = 38.44 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 shown Momentary Values	2	85.23		11250	0			— 3.71	+75°L	18	20.60	5.86
	3	86.16		14700	0			— 0.00	+70°L	16	18.50	5.81
	4	88.12		10000	0			— 6.45	+65°L	19	22.00	6.40
	5	90.00		6500	0			8.47	+50°L	37	24.00	5.88
	6	91.25		5750	0			8.54	+65°L	20	27.50	5.51
	8	95.82		5850	+0.0465			—24.35	+85°L	13	31.50	7.14
	9	100.71		25300	0			+ 8.90	+60°L	22	11.00	6.62
	10	101.48		21900	−0.0101			+10.20	+90°L	14	11.35	5.84
	11	103.69		29000	−0.0500			+27.80	+70°L	14	10.50	6.14
	12	103.60		30100	0.0545			+28.90	+75°L	13	10.00	6.11
	13	103.89		25500	—0.0500			+22.60	+70°L	16	14.00	6.20
	14	104.53		19900	−0.0388			+15.50	—85°L	16	16.90	5.66
	15	104.41		21850	−0.0388			+15.64	85°L	12	15.80	6.38
	16	105.71		12250	0			4.05	+85°L	10	27.20	6.37
	17	106.30		14250	+0.0325			—12.10	+65°L	9	25.30	7.11
	18	106.00		12750	+0.0325			—14.72	+60°L	12	27.00	7.53
	19	96.00		5350	+0.0550			—27.05	+80°L	11	30.30	7.14
	20	95.65		3500	+0.0425			28.70	+80°L	17	32.50	8.25
Section Columns 5, 6, and 9 to 13 show Average Values	1	82.41 − 82.00	2152	17300		20.10	19.40	+ 2.20	+45°L	9	20.00	6.89
	2	87.56 − 86.80	4348	16100		22.10	21.32	— 0.66	+65°L	12	20.40	7.15
	3	89.10 − 88.59	2372	9000		23.40	22.70	1.90	+50°L	21	23.20	5.22
	4	92.00 − 91.25	3970	6500		26.30	27.20	− 11.43	+65°L	20	26.80	6.02
	5	94.13 − 93.63	2624	6600		27.15	27.33	—13.55	+80°L	21	26.90	7.49
	6	95.30 − 95.10	988	3400		33.55	33.95	20.80	+60°L	14	33.75	7.90
	7	101.50 101.00	2620	24000		11.60	10.70	+12.23	+90°L	14	11.20	5.38
	8	105.74 − 105.34	2088	19150		21.90	21.90	+ 2.79	+70°L	16	21.90	6.51
	9	104.40 − 104.10	1580	24500		16.30	16.30	+13.35	−85°L	15	16.80	6.13
	10	105.72 − 105.42	1640	12500		27.30	26.50	+ 2.90	−85°L	10	27.30	5.63
	11	111.16 − 110.86	1600	35800		5.10	5.10	+19.80	−80°L	13	5.10	6.60
	12	116.00 − 115.50	2240	17200		17.10	17.00	+ 2.24	—85°L	13	17.10	6.08

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* For complete table heading see Table 36, p. 99.

TABLE 40 TEST NO. S-1018*

From Gilman to Champaign, May 2, 1908. Weather: Fair. Temperature: 40° F. at start, 45° F. at end of test. Total weight behind measuring drawbar = 1353 tons, including the test car. Train length = 2130 ft. Center of mass 1000 ft. back of measuring drawbar. 49 cars: 34 empty, 15 loaded. Kind of cars: 28 box, 3 gondola, 8 flat, 8 tank, 1 test, 1 caboose, and 2 I. C. locomotives, No. 423 and No. 732 with tenders. Average weight per car = 25.40 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	5	93.94		13300	0			+8.92	+85°R	15	16.00	6.47
	6	94.59		14600	0			+10.90	+70°R	12	14.70	6.67
	7	96.34		20600	—0.0018			+26.50	+55°R	7	10.60	5.32
	8	97.29		14750	—0.0042			+9.30	+45°R	13	17.95	7.78
	9	98.68		22000	—0.0048			+28.80	+60°R	8	9.45	5.82
	10	100.15		18500	—0.0025			+22.00	+85°R	14	13.10	5.57
	11	102.00		9470	+0.0159			—8.90	+75°R	13	24.80	8.83
	12	104.43		4750	—0.0263			—20.10	+10°R	23	30.20	8.59
	13	105.34		5000	—0.0046			—10.15	+65°R	14	29.30	8.00
	14	106.25		7000	—0.0419			+7.44	+45°R	12	26.30	6.40
	15	106.40		8300	—0.0645			+13.90	+50°R	11	25.70	7.12
	16	106.53		8550	—0.0644			+15.40	+55°R	10	21.20	6.72
	17	106.64		9350	—0.0596			+15.60	+60°R	11	23.15	6.77
	18	106.71		10250	—0.0419			+14.37	+60°R	10	22.50	6.18
	19	106.90		10000	—0.0419			+12.15	+45°R	11	21.00	6.85
	20	107.07		11000	—0.0419			+14.38	+45°R	9	19.70	6.74
	21	107.47		12000	—0.0419			+17.10	+45°R	8	17.00	6.44
	22	108.23		16000	0			+16.10	+45°R	7	13.80	5.72
	23	109.17		8750	0			—2.72	+45°R	10	21.50	7.50
	26	115.94		9200	0			—5.70	+35°R	12	23.20	7.00
Section Columns 5, 6, and 9 to 13 show Average Values	3	92.00—92.51	2675	12800		16.20	15.20	+11.20	+80°R	13	15.80	6.00
	4	96.22—96.74	2770	21250		11.30	11.30	+25.50	+55°R	7	11.40	6.02
	5	104.43—105.34	4800	5100		29.70	29.20	—11.30	+65°R	14	29.50	9.62
	8	126.00—126.45	2400	9600		18.20	17.70	+3.08	+60°R	12	17.68	6.46
	11	98.55—98.85	1588	22000		10.35	10.12	+25.70	+6°0R	8	9.40	6.72
	12	101.70—102.00	1584	10100		23.41	24.77	—11.00	+75°R	13	24.00	8.74
	13	108.08—108.41	1748	15000		11.20	14.00	+16.30	+45°R	7	14.20	5.21
	14	106.00—107.30	6840	9300		28.05	18.23	+12.50			22.80	6.82
	15	106.00—106.53	2750	7500		28.05	24.32	+7.88			26.60	7.59
	16	106.53—107.30	4096	10500		24.32	28.23	+15.10			20.90	6.52

* For complete table heading see Table 36, p. 99.

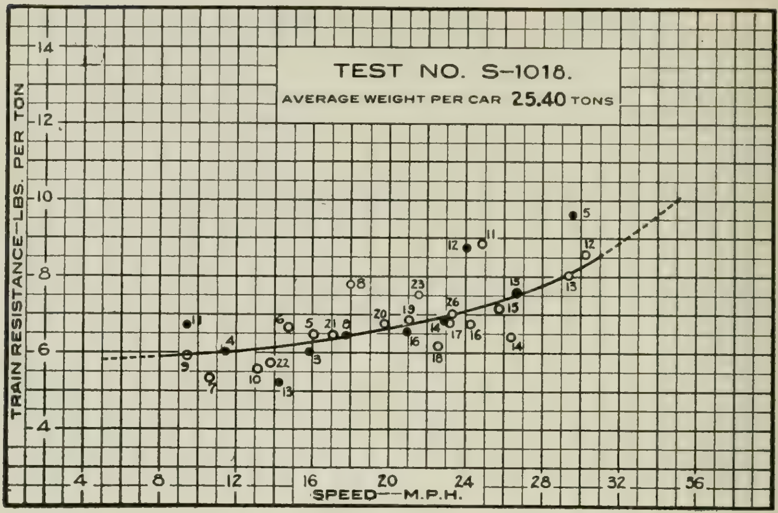
TEST NO. S-1018.
AVERAGE WEIGHT PER CAR 25.40 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
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FIG. 23

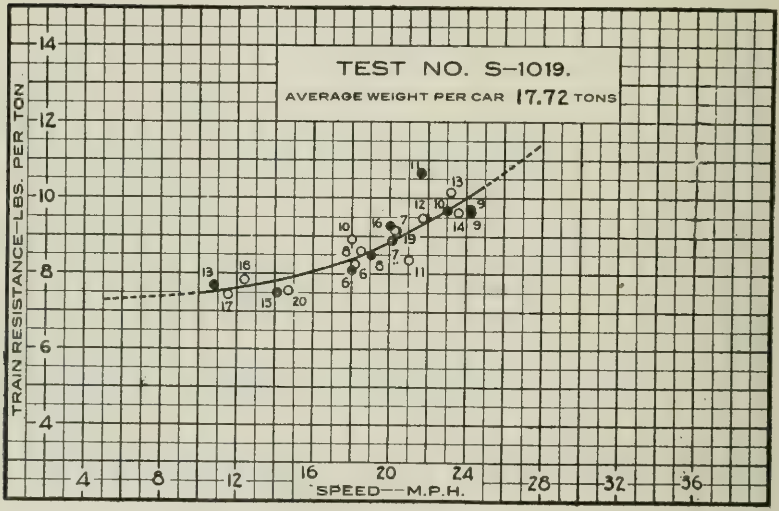
TEST NO. S-1019.
AVERAGE WEIGHT PER CAR 17.72 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
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FIG. 24

TABLE 41 TEST NO. S-1019*

From Champaign to Mattoon, May 9, 1908. Weather: Fair. Temperature: 44° F. at start, 62° F. at end of test. Total weight behind measuring drawbar = 1572 tons, excluding the test car. Train length = 3480 ft. Center of mass 1600 ft. back of measuring drawbar. 89 cars: 75 empty, 14 loaded. Kind of cars: 29 box, 52 gondola, 6 flat, 1 tank, 1 caboose. Average weight per car = 17.72 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	6	141.18		10700	0			− 3.75	+30° R	21	18.20	8.23
	7	143.80		9000	0			− 9.03	+25° R	27	20.25	9.14
	8	144.90		11000	0			− 4.16	+30° R	21	18.50	8.58
	9	147.30		7500	0			−12.70	+20° R	30	24.30	9.61
	10	149.80		11800	0			− 3.64	+30° R	21	18.00	8.89
	11	145.98		9000	+0.0289			−14.52	+20° R	31	21.00	8.36
	12	146.19		8700	+0.0289			−17.95	+20° R	31	21.75	9.46
	13	146.38		8050	+0.0240			−19.50	+35° R	21	23.20	10.14
	14	146.54		7400	+0.0289			−20.50	+20° R	31	23 60	9.62
	17	157.13		16000	0			+ 7.21	+25° R	18	11.56	7.44
	18	159.82		15400	0			+ 5.22	+25° R	18	12.45	7.82
	19	161.44		9800	0			− 7.66	+20° R	32	20.30	9.13
	20	165.93		13250	0			+ 2.30	+45° R	15	14.70	7.54
Section Columns 5, 6, and 9 to 13 show Average Values	6	141.18—141.56	2370	10900		17.90	17.90	− 3.03	+30° R	21	18.00	8.09
	7	143.80—144.27	2450	9200		20.20	20.00	− 7.33	+25° R	27	20.10	8.86
	8	144.89—145.44	2890	10200		18.50	19.50	− 7.80	+30° R	21	19.00	8.49
	9	146.98—144.47	2568	7000		24.25	24.25	−13.76	+20° R	30	24.25	9.67
	10	146.19—146.54	1856	8250		21.54	23.86	− 7.90	+20° R	31	23.00	9.67
	11	145.99—146.38	2064	8850		20.85	23 18	− 8.90	+20° R	31	21.65	10.66
	13	155.83—156.33	2640	18000		10.78	10.78	+ 9.90	+35° R	19	10.78	7.70
	15	165.66—166.16	2640	12950		14.00	14.00	+ 2.00	+30° R	21	14.10	7.48
	16	161.21—161.61	2112	10100		19.83	19.97	− 3.20	+20° R	32	20.00	9.26

*For complete table heading see Table 36, p. 99.

TABLE 42 TEST NO. S-1021*

From Rantoul to Paxton. May 13, 1908. Weather: Continuous Rain. Temperature: 66° F. at start, 70° F. at end of test. Total weight behind measuring drawbar = 2908 tons, including the test car. Train length = 2400 ft. Center of mass 1200 ft. back of measuring drawbar. 63 cars: 10 empty, 53 loaded. Kind of cars: 18 box, 38 gondola, 3 flat, 2 tank, 1 test, 1 caboose. Average weight per car = 46.16 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	7	106.79		10500	+0.0362			−16.70	+75°R	13	26.60	6.55
	8	105.82		10800	−0.0056			− 6.60	+80°R	15	29.90	6.74
	9	105.74		12050	−0.0172			− 3.96	+80°R	15	29.60	7.26
	10	104.65		18650	−0.0490			+15.80	+65°R	16	23.25	5.02
	11	104.59		19000	−0.0190			+16.05	+70°R	15	22.80	5.06
	12	104.53		20850	−0.0490			+16.30	+70°R	16	22.25	5.61
	13	104.41		21300	−0.0425			+15.20	+70°R	15	21.35	5.57
	14	104.32		21100	−0.0425			+14.10	+70°R	17	20.75	5.92
	15	104.21		21300	−0.0425			+14.08	+80°R	18	19.85	5.99
	16	104.10		21800	−0.0425			+16.90	+70°R	20	19.00	5.08
	17	103.62		28900	−0.0540			+28.60	+75°R	19	13.60	4.30
	18	103.50		30750	−0.0530			+29.50	+60°R	16	10.40	4.24
	19	103.72		27750	−0.0583			+27.90	+65°R	22	14.70	5.46
	20	105.40		12200	−0.0490			+ 5.94	+80°R	15	28.50	6.55
	21	104.82		17250	−0.0490			+11.90	+80°R	18	24.50	5.94
	22	106.84		10750	+0.0362			−17.40			26.40	6.90
	23	105.95		11500	+0.0156			−13.00			29.80	7.11
Section Columns 5, 6, and 9 to 13 show Average Values	7	107.04—106.73	1596	10850		25.44	26.92	−14.00	+75°R	12	26.20	7.03
	8	106.30—106.00	1588	11200		28.75	29.75	−13.20	+75°R	15	29.50	7.63
	9	106.00—105.70	1588	11150		29.75	29.75	− 6.60	+80°R	15	29.80	6.99
	10	105.70—105.40	1584	11650		29.75	28.40	+ 2.40	+80°R	15	29.00	6.29
	11	105.40—105.10	1592	13700		28.40	26.43	+ 6.07	+80°R	15	27.40	6.50
	12	105.10—104.80	1584	16500		26.43	24.32	+ 7.70	+80°R	18	25.40	6.66
	13	104.80—104.49	1588	18500		24.32	22.07	+13.20	+70°R	16	23.20	4.60
	14	104.49—104.19	1580	21350		22.07	19.80	+11.10	+70°R	16	20.90	6.16
	15	104.19—103.89	1576	22300		19.08	17.00	+13.50	+70°R	20	18.40	5.69
	16	103.89—103.59	1600	26600		17.00	12.95	+27.75	+65°R	22	15.00	3.87
	17	103.50—103.33	868	32500		11.52	8.45	+30.00			10.00	4.69
	18	103.33—103.21	648	35250		8.45	6.41	+30.00			7.40	3.99
	19	103.21—103.12	464	36750		6.41	4.50	+30.00			5.50	1.38
	20	103.12—103.03	512	37600		4.50	1.64	+30.00			3.00	3.94

* For complete table heading see Table 36, p. 99.

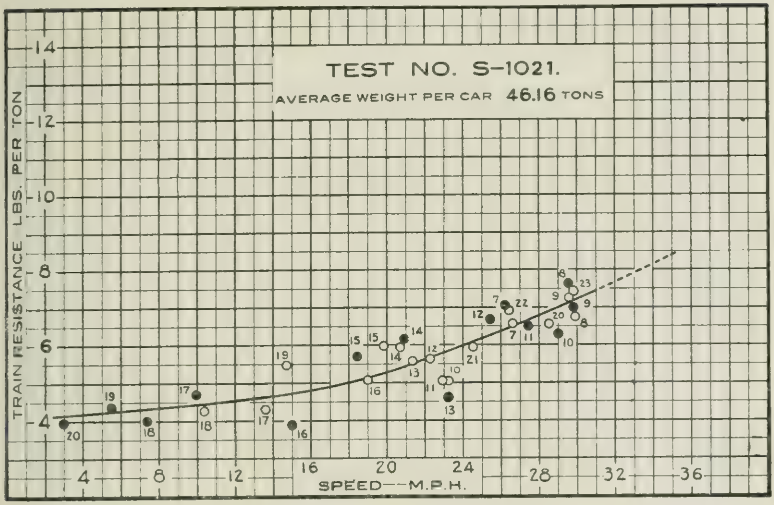
TEST NO. S–1021.
AVERAGE WEIGHT PER CAR 46.16 TONS
TRAIN RESISTANCE LBS. PER TON
SPEED—M.P.H.
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Fig. 25

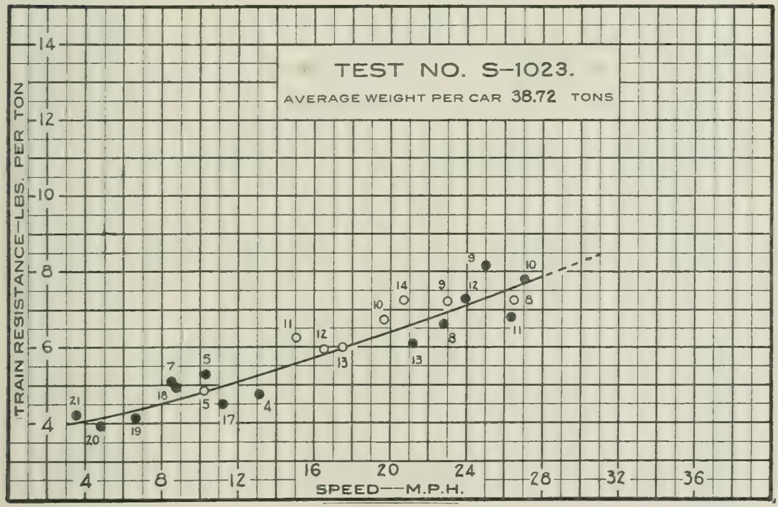
TEST NO. S–1023.
AVERAGE WEIGHT PER CAR 38.72 TONS
TRAIN RESISTANCE–LBS. PER TON
SPEED—M.P.H.
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Fig. 26

TABLE 43 TEST NO. S-1023*

From Champaign to Paxton, May 23, 1908. Weather: Fair. Temperature: 62° F. at start, 74° F. at end of test. Total weight behind measuring drawbar = 2243 tons, including the test car. Train length = 2320 ft. Center of mass 1020 ft. back of measuring drawbar. 58 cars: 17 empty, 41 loaded. Kind of cars: 24 box, 30 gondola, 2 tank, 1 test, 1 caboose. Average weight per car = 38.72 tons.

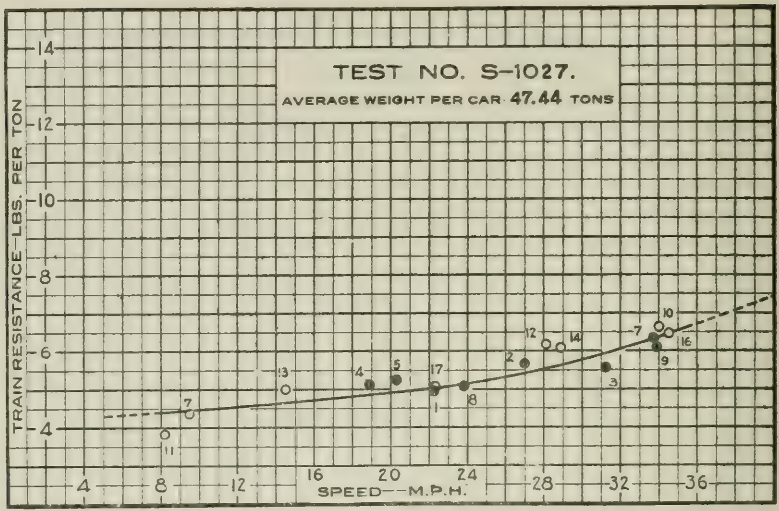
1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	5	114.00		18400	0			+ 8.88	+85° R	15	10.20	4.84
	8	106.71		10300	+0.0360			−16.00	+80° R	18	26.50	7.24
	9	104.91		12500	−0.0600			+10.70	+85° R	17	23.00	7.19
	10	104.48		17000	−0.0500			+16.03	−80° R	17	19.65	6.71
	11	103.98		20600	−0.0500			+20.30	+75° R	19	15.00	6.22
	12	104.04		19200	−0.0400			+17.80	−90° R	18	16.50	5.94
	13	104.12		18500	−0.0400			+16.00	−85° R	20	17.50	5.97
	14	104.67		14850	0.0675			+15.28	+90° R	17	20.68	7.23
Section Columns 5, 6, and 9 to 13 show Average Values	4	116.50–116.00	2640	14700		13.10	13.10	+ 4.81	90° R	13	13.10	4.73
	5	114.71–114.21	2640	18600		10.30	10.30	+ 7.92	+85° R	15	10.30	5.30
	7	110.88–110.38	2240	29000		8.50	8.50	+20.70	+80° R	15	8.50	5.10
	8	108.95–108.56	2104	9700		23.86	21.45	+ 3.38	90° R	17	22.80	6.64
	9	107.21–106.71	2644	11250		23.60	26.43	+ 18.15	+80° R	18	25.05	8.18
	10	106.71–106.21	2616	10550		26.43	28.05	+ 14.30	+80° R	18	27.00	7.78
	11	105.47–105.17	1584	10850		27.27	25.10	+ 8.00	+85° R	25	26.30	6.78
	12	105.17–104,87	1580	12050		25.10	22.60	+ 9.01	+85° R	17	23.90	7.18
	13	104.87–104.57	1584	14450		22.60	19.65	+15 30	+85° R	17	21.20	6.07
	17	103.81–103.64	920	25650		11.86	9.28	+29.30			11.20	4.48
	18	103.64–103.50	716	28150		9.28	7.24	+28.75			8.72	4.92
	19	103.50–103.40	546	30000		7.24	5.46	+31.90			6.66	4.17
	20	103.40–103.32	394	31850		5.46	3.82	+34.20			4.80	3.93
	21	103.32–103.27	292	33200		3.82	2.59	+32.90			3.56	4.21

* For complete table heading see Table 36, p. 99.

TABLE 44 TEST NO. S-1027

From Champaign to Gilman, July 2, 1908. Weather: Intermittent rain. Temperature: 64° F. at start, 80° F. at end of test. Total weight behind measuring drawbar = 2185 tons, including the test car. Train length = 1710 ft. Center of mass 800 ft. back of measuring drawbar. 46 cars: 3 empty, 43 loaded. Kind of cars: 8 box, 35 gondola, 1 flat, 1 test, 1 caboose. Average weight per car = 47.44 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method of Calculation	Item No.	Location on Road Milepost No.	Length of Section feet	Total Drawbar Pull pounds	Acceleration miles per hour per second	Speeds At Entrance to Section m. p. h.	Speeds At Exit from Section m. p. h.	Grade + Up — Down feet per mile	Wind Approximate Direction	Wind Approximate Velocity m. p. h.	Speed m. p. h.	Net Train Resistance pounds per ton
				P	A	V_1	V_2	G			V	R
Point Columns 5, 6, and 9 to 13 show Momentary Values	7	110.51		25900	0			+19.72	—50°R	9	9.50	4.37
	10	105.91		6900	0			— 9.16	90°R	13	34.00	6.63
	11	103.00		29700	—0.0054			+27.20	—55°R	5	8.20	3.81
	12	101.91		8100	0			— 6.54	90°R	17	28.10	6.16
	13	100.57		14400	0			+ 4.11	—70°R	15	14.50	5.00
	14	99.49		5300	0			— 9.56	—85°R	11	28.90	6.08
	16	97.10		3750	+0.0420			—22.90	—85°R	16	34.50	6.46
	17	86.03		10000	0			— 1.32	—70°R	22	22.30	5.06
Section Columns 5, 6, and 9 to 13 show Average Values	1	85.40— 86.30	2430	9900		22.30	22.30	— 1.09	—70°R	22	22.25	4.94
	2	87.85— 88.45	3215	6600		27.10	27.10	— 6.94	—75°R	15	27.00	5.65
	3	89.81— 90.56	3955	4500		31.25	31.25	— 9.22	—80°R	15	31.25	5.54
	4	115.56—116.17	3280	12800		19.00	19.00	+ 1.98	—60°R	12	18.90	5.11
	5	117.10—117.93	4440	11650		20.20	20.20	+ 0.27	—60°R	12	20.30	5.22
	7	106.11—105.51	3220	9100		33.40	32.85	— 4.09	90°R	13	33.75	6.33
	8	98.88—98.29	3080	9050		22.90	24.70	+ 7.55	+70°R	10	23.80	5.08
	9	97.61—96.72	4720	4200		31.90	31.25	—17.00	+85°R	16	33.87	6.09


TEST NO. S-1027.
AVERAGE WEIGHT PER CAR 47.44 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36
1
2
3
4
5
7
7
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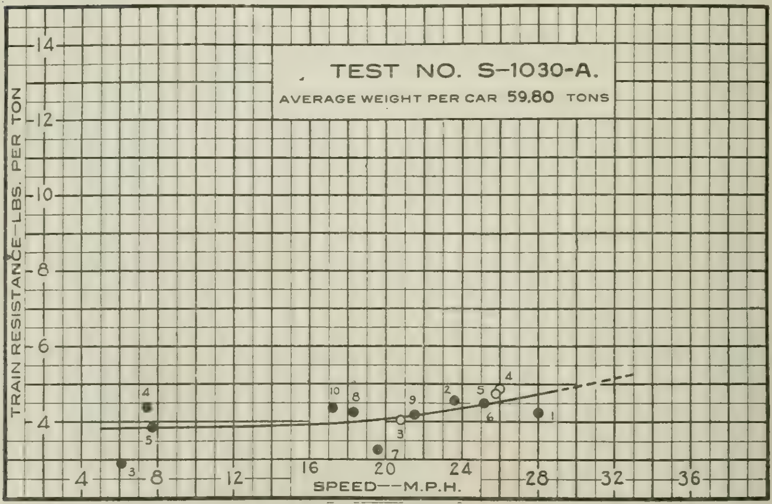
14
16
17

FIG. 27


TEST NO. S-1030-A.
AVERAGE WEIGHT PER CAR 59.80 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36
1
2
3
3
4
4
5
5
6
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9
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FIG. 28

TABLE 45 TEST No. S-1030A

From Effingham to Mattoon, July 8, 1908. Weather: Fair. Temperature: 60° F. at start, 68° F. at end of the test. Total weight behind measuring drawbar = 2036 tons, including the test car. Train length = 1380 ft. Center of mass 690 ft. back of measuring drawbar. 34 cars: 2 empty, 32 loaded. Kind of cars: 32 gondola, 1 test, 1 caboose. Average weight per car = 59.88 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method of Calculation	Item No.	Location on Road Milepost No.	Length of Section feet	Total Drawbar Pull pounds	Acceleration miles per hour per second	Speeds		Grade + Up — Down feet per mile	Wind		Speed m. p. h.	Net Train Resistance pounds per ton
						At Entrance to Section m. p. h.	At Exit from Section m. p. h.		Approximate Direction	Approximate Velocity m. p. h.		
				P	*A*	V_1	V_2	*G*			*V*	*R*
Point Columns 5, 6, and 9 to 13 show Momentary Values	3	190.35		13200	—0.0690			+23.40	+50°R	8	20.80	4.04
	4	193.16		9050	—0.1350			+32.10	+55°R	9	26 03	4.90
	5	193.61		11000	+0.1390			—32.40	+60°R	5	25.80	4.77
Section Colums 5, 6, and 9 to 13 show Average Values	1	174.50—173.88	3280	160		26.20	30.00	—22.70	+20°R	6	28.00	1.23
	2	175.00—174.50	2600	5620		20.71	26.20	—22.70	+20°R	6	23.60	4.57
	3	176 97—176.70	3500	30050		6.54	6.00	+31.50	+20°R	3	6.12	2.91
	4	177.58—176.97	3212	30650		10.22	6.54	+31 50	+20°R	3	7.14	4.39
	5	178.00—176.70	8956	28800		16.15	6.00	+31.50	+20°R	3	7.65	3.87
	6	181.50—180.37	5144	12050		23.92	26.10	0	+50°R	7	25.20	4.46
	7	190.01—189.36	3452	12000		19.20	20.05	+ 5.10	+55°R	9	19.60	3.29
	8	191.72—191.41	1576	15000		17.18	19.14	0	+55°R	8	18.30	4.25
	9	193.16—192.71	2360	11550		26.03	17.58	+32.10	+60°R	5	21.50	4.20
	10	196.19—195.81	2140	14900		17.30	17.18	+ 7.70	+65°R	6	17.20	4.39

TABLE 46 TEST NO. S-1030B*

From Mattoon to Champaign, July 8, 1908. Weather: Fair. Temperature: 68° F. at start, 72° F. at end of test. Total weight behind measuring drawbar = 2342 tons, including the test car. Train length = 1650 ft. Center of mass 900 ft. back of measuring drawbar. 41 cars: 3 empty. 38 loaded. Kind of cars: 6 box, 33 gondola, 1 test, 1 caboose. Average weight per car = 57.12 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	3	167.46		7200	0			−1 .92			26.60	3.80
	5	165.52		6500	0			3 .20			28.90	3.97
	6	164.45		8060	0			2 .88	+20° R	12	28.40	4.53
	9	159.74		13900	0			+5 .12	+20 R	7	15.25	4.00
	10	157.80		18100	+0.0356			+5 .12	+25° R	6	12.30	4.23
	11	157.75		17000	+0.0356			+1 .12	+25° R	6	13.00	3.50
	12	157.57		16200	+0.0356			−0 .54	+35° R	6	14.20	3.93
	13	158.06		23600	+0.0457			+5 .60	+65° R	3	8.30	3.70
	14	157.94		21500	+0.0457			+2 .56	+30° R	5	10.70	3.96
	21	164.15		7200	+0.0700			−21.10	+30° R	9	28.50	4.48
Section Columns 5, 6 and 9 to 13 show Average Values	1	166.62—167.06	2315	8000		25.80	25.80	2.12			25.50	4.22
	2	164.45—164.95	3164	7350		27.40	27.00	0.84	+20 R	12	27.15	3.93
	3	158.72—159.25	2815	2500		17.30	17.30	7.82	+65 R	4	16.90	4.02
	4	155.44—154.81	3300	7550		27.10	28.90	−8.96	+20° R	12	28.10	4.52
	5	152.25—152.88	3270	14200		17.50	17.50	+6.14			17.00	3.73
	6	149.04—148.20	4396	11800		21.40	23.00	0.66			22.20	4.18
	7	143.32—143.92	3150	14000		16.30	16.30	+5.48			16.60	3.91
	8	140.49—141.23	3912	11950		19.63	19.25	+3.77			19.75	3.89
	9	132.65—131.68	5084	8500		26.75	25.26	0			26.05	4.68
	10	145.06—144.48	3068	16950		12.48	13.63	+7.65			13.10	3.65
	11	158.06—157.80	1400	20850		8.46	12.55	+3.40	+65° R	3	10.60	3.41
	12	157.80—157.57	1200	17500		12.55	14.58	+0.66	+25° R	6	13.70	4.08
	13	162.33—161.87	2416	8730		23.70	24.40	4.36	+20° R	9	23.50	3.59
	14	149.65—148.97	3280	12400		21.53	21.30	+4.20			21.30	3.87

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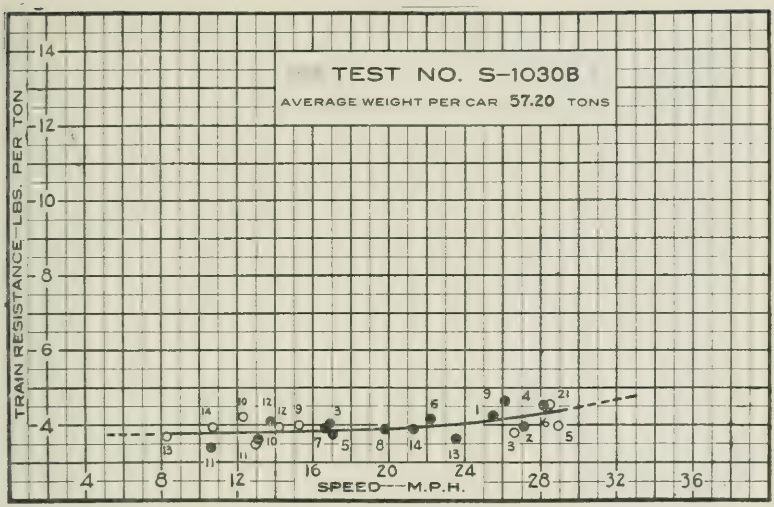
*For complete table heading see Table 36. p. 99.


TEST NO. S-1030B
AVERAGE WEIGHT PER CAR 57.20 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
14
12
10
8
6
4
4
8
12
16
20
24
28
32
36
14
10
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12
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FIG. 29

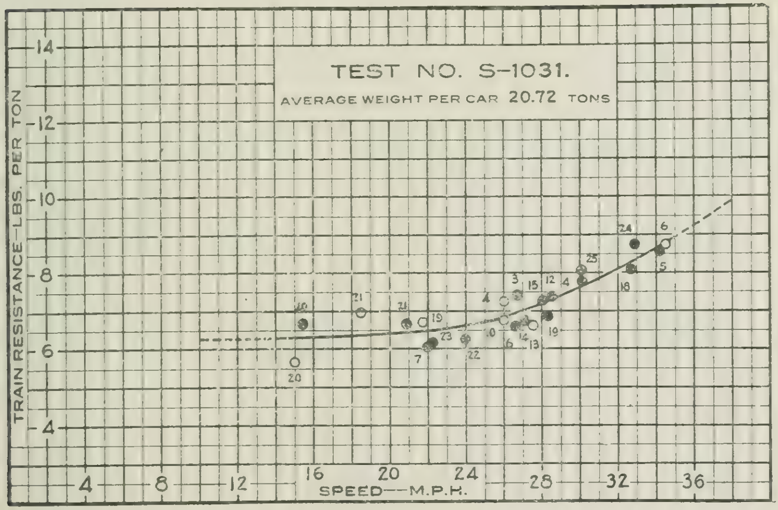
TEST NO. S-1031.
AVERAGE WEIGHT PER CAR 20.72 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
14
12
10
8
6
4
4
8
12
16
20
24
28
32
36
20
21
21
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FIG. 30

TABLE 47 TEST NO. S-1031*

From Champaign to Dorans, July 22, 1908. Weather: Fair. Temperature: 70° F. at start, 82° F. at end of test. Total weight behind measuring drawbar = 747 tons, excluding the test car. Train length = 1425 ft. Center of mass 1000 ft. back of measuring drawbar. 36 cars: 30 empty, 6 loaded. Kind of cars: 33 box, 1 gondola, 1 flat, 1 caboose. Average weight per car = 20.72 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	4	142.06		4700	−0.0204			− 1.50	+ 0°	5	26.00	7.25
	6	147.10		2600	0			−13.84	+ 0°	7	34.50	8.73
	10	159.81		4200	0			− 3.01	+ 0°	6	26.00	6.76
	13	163.09		4400	0			− 1.89	+ 0°	7	27.50	6.60
	19	166.83		7900	0			+10.20	+ 0°	2	21.75	6.70
	20	164.40		12400	+0.0275			+21.80	+40°L	4	15.00	5.68
	21	164.75		9650	+0.0550			+ 1.50	+40°L	4	18.50	6.95
Section Columns 5, 6, and 9 to 13 show Average Values	3	139.57—140.36	4180	4350		26.70	26.70	− 4.13	+ 0°	5	26.70	7.40
	4	143.90—144.25	4460	3900		29.75	29.75	− 6.81	+ 0°	5	30.10	7.76
	5	146.68—147.51	4405	2500		33.90	33.90	−13.65	+ 0°	7	34.20	8.53
	6	151.94—152.77	4390	4950		26.60	26.60	+ 0.18	+ 0°	4	26.60	6.56
	7	155.70—156.45	4016	7100		22.00	22.00	+ 9.60	+ 0°	4	22.00	6.01
	12	149.00—149.53	2760	4650		28.36	27.77	− 0.77	+ 0°	7	28.50	7.36
	14	153.88—154.74	4568	4380		27.61	25.62	+ 2.14	+ 0°	5	27.10	6.72
	15	160.31—160.78	2468	4450		25.95	28.94	−16.15	+ 0°	7	28.00	7.24
	18	147.51—148.35	4412	2900		33.53	31.36	− 5.04	+ 0°	7	32.70	8.07
	19	153.20—153.87	3528	4470		28.30	28.30	− 2.25	+ 0°	5	28.30	6.85
	20	164.40—164.74	1812	11800		15.00	18.00	+13.70	+ 0°	1	15.40	6.69
	21	164.74—165.50	3980	7700		18.00	22.75	+ 0.40	+ 0°	1	20.90	6.65
	22	159.63—159.16	2464	5500		24.80	23.65	+ 7.30	+ 0°	5	24.00	6.22
	23	157.40—158.36	5064	5450		22.60	23.85	+ 0.94	+ 0°	5	22.30	6.11
	24	146.17—146.68	2652	3000		31.90	33.50	−19.90	+ 0°	7	32.90	8.74
	25	161.24—161.62	2014	4100		30.50	30.50	− 6.84	+ 0°	6	30.50	8.09

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* For complete table heading see Table 36, p. 99.

TABLE 48 TEST NO. S-1033*

From Champaign to Gilman, Sept. 26, 1908. Weather: Fair. Temperature: 66° F. at start, 82° F. at end of test. Total weight behind measuring drawbar = 2275 tons, including the test car. Train length = 1710 ft. Center of mass 850 ft. back of measuring drawbar. 44 cars: 2 empty, 42 loaded. Kind of cars: 42 gondola, 1 test, 1 caboose. Average weight per car = 51.70 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	9	111.08		26050	0			+20.20	+0°	5	8.15	3.79
	10	110.72		25150	0			+19.45	+0°	5	9.75	3.68
	12	104.13		23900	0			+16.98	+5° R	7	12.00	4.07
	13	98.18		6000	+0.4066			31.50	+5° L	12	29.35	4.26
	17	93.63		2700	0			9.88	+5° R	12	40.00	4.93
	18	90.42		3850	0			10.49	+5° L	17	39.40	5.67
	20	85.88		6150	0			— 4.02	+0°	16	31.75	4.35
	21	83.40		6800	0			— 3.40	+5° L	15	31.75	4.28
Section Columns 5, 6, and 9 to 13 show Average Values	2	118.27—117.19	5688	11300		23.60	24.10	+ 0.28	+15° R	7	24.25	4.57
	3	111.30—110.60	3684	25900		8.98	8.98	+20.20	+ 0°	5	8.98	3.72
	4	101.91 103.91	5260	24000		11.21	11.21	+16.30	+ 5 R	7	11.21	4.37
	5	101.66—100.97	3660	12400		22.85	18.75	+10.96	+10° R	15	20.79	4.50
	6	98.19 - 97.14	5512	5000		29.20	37.25	—25.87	+ 5° L	14	34.17	5.33
	7	94.07— 93.24	4400	3200		40.00	40.00	9.24	+ 5° R	12	40.00	4.91
	8	96.25— 95.58	3556	3200		37.85	42.10	—28.80	+ 5° L	22	40.40	5.78
	9	90.66— 90.00	3492	4150		38.95	39.85	10.43	+ 5° L	17	39.68	4.38
	10	89.24— 88.76	2504	4950		38.30	37.40	1.90	+ 5° L	10	37.94	4.77
	11	83.80— 83.40	2096	6600		31.25	31.58	— 5.04	+ 5° R	14	31.75	4.19
	12	116.00—115.36	3400	11800		23.00	22.10	+ 3.99	+ 5° R	7	23.20	4.23
	13	111.67—111.27	2108	11800		19.50	18.85	+ 8.55	+ 5° R	7	19.20	4.07
	14	103.91—103.41	2600	29900		10.72	5.81	+29.20	+ 5° R	7	6.33	4.20
	15	97.11 96.25	4700	1200		37.50	38.00	10.80	+ 5° L	22	37.70	5.40
	16	83.80— 83.05	3930	2900		32.05	31.10	— 5.78	+ 0°	15	31.50	4.53
	17	88.77 - 88.00	4076	5200		37.53	37.05	— 5.12	+ 5° L	17	37.30	4.84

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* For complete table heading, see Table 36, p. 99.

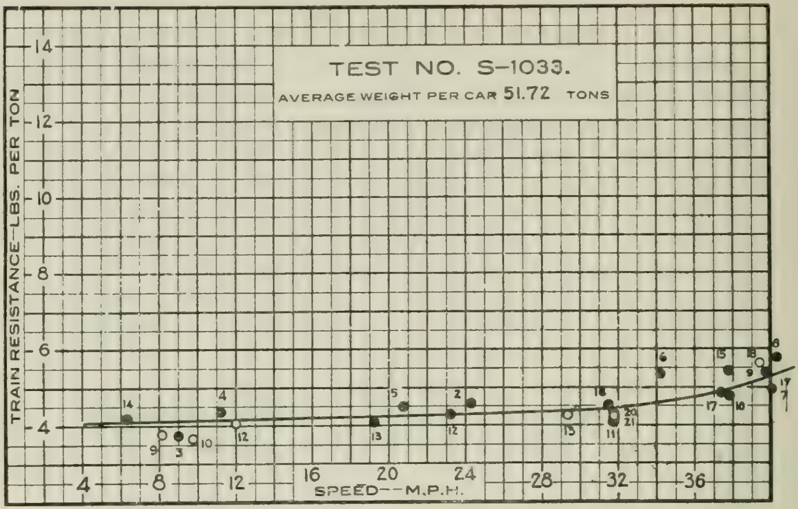
TEST NO. S-1033.
AVERAGE WEIGHT PER CAR 51.72 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36

FIG. 31

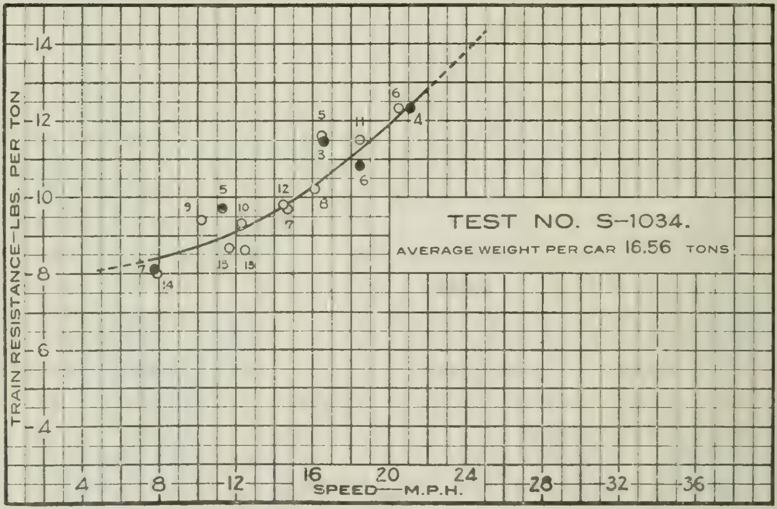
TEST NO. S-1034.
AVERAGE WEIGHT PER CAR 16.56 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36

FIG. 32

TABLE 49 TEST No. S-1034

From Champaign to Mattoon, October 3, 1908. Weather: Fair. Temperature: 42° F. at start, 60° F. at end of test. Total weight behind measuring drawbar = 1259 tons, excluding the test car. Train length = 3015 ft. Center of mass 1500 ft. back of measuring drawbar. 76 cars: 76 empty, 0 loaded. Kind of cars: 75 gondola, 1 caboose. Average weight per car = 16.56 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method of Calculation	Item No.	Location on Road Milepost No.	Length of Section feet	Total Drawbar Pull pounds	Acceleration miles per hour per second	Speeds At Entrance to Section m. p. h.	Speeds At Exit from Section m. p. h.	Grade + Up − Down feet per mile	Wind Approximate Direction	Wind Approximate Velocity m. p. h.	Speed m. p. h.	Net Train Resistance pounds per ton
				P	A	V_1	V_2	G			V	R
Point Columns 5, 6, and 9 to 13 show Momentary Values	5	143.80		10000	0			−9.64	−55°L	5	16.50	11.59
	6	146.89		7900	0			−15.94	−80°L	5	20.50	12.28
	7	149.30		11800	0			−0.84	55°L	1	14.70	9.70
	8	153.44		10300	0			−5.25	80°L	2	16.10	10.17
	9	156.22		16140	0			+9.52	−30°L	3	10.25	9.45
	10	159.72		14400	0			+5.52	+85°L	1	12.25	9.35
	11	161.05		9150	0			−12.20	0°	1	18.25	11.49
	12	165.81		13000	0			+1.40	−50°L	5	11.50	9.79
	13	166.80		15550	0			+9.81	75°L	3	12.25	8.62
	14	168.45		17600	0			+15.75	−60°L	1	7.90	8.00
	15	167.93		12500	0			+3.41	90°L	5	11.60	8.65
Section Columns 5, 6, and 9 to 13 show Average Values	3	142.97—143.80	4373	10700		15.60	16.50	−9.48	−55°L	5	16.56	11.45
	4	146.40—147.54	6027	7800		21.00	21.00	−16.12	80°L	5	21.10	12.31
	5	154.78—155.70	4878	16000		11.25	11.25	+7.96	−15°L	5	11.27	9.69
	6	160.77—161.53	4058	9100		17.50	17.50	−9.37	+85°L	4	18.44	10.78
	7	168.22—168.74	2741	18000		7.25	7.90	+15.57	−60°L	4	7.80	8.12

TABLE 50   TEST NO. S-1036*

From Champaign to Gilman, October 10, 1908. Weather: Fair. Temperature: 40° F. at start, 62° F. at end of test. Total weight behind measuring drawbar — 1961 tons, including the test car. Train length = 2010 ft. Center of mass 966 ft. back of measuring drawbar. 52 cars: 8 empty, 44 loaded. Kind of cars: 36 box, 13 gondola, 1 flat, 1 test, 1 caboose. Average weight per car = 37.72 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values.	6	111.03		24350	0			+20.30	−15°R	5	9.14	4.71
	7	103.06		30450	0			+30.10	−45°R	3	5.73	4.12
	8	95.32		3300	0			−17.60	+70°R	11	36.65	8.35
	9	93.75		3200	0			−11.55	+75°R	8	31 50	6.01
	10	92.16		1800	0			−11.80	+80°R	7	29.15	5.39
	11	90.02		5500	0			− 8.90	+55°R	7	29.50	6.17
	12	86.10		8750	0			− 0.50	+25°R	3	21.60	4 65
	13	83.51		7400	0			− 4.70	+15°R	5	24.75	5.55
	14	81.38		5800	0			− 5.00	+35°R	4	22.50	4.85
	15	101.14		14800	−0.0140			+16.03	−65°R	5	18.14	5.65
	16	103.67		20150	−0.0620			+28.90	−40°R	9	12.90	5.20
	19	111.20		23900	−0.0260			+24.96	−15°R	4	9.90	5.19
	21	117.18		11800	0			+ 0.79	−50°R	4	16 23	6.32
	23	114.26		15100	−0.0070			+ 8,93	60°R	5	12 54	4.99
	26	103.62		23450	−0.0440			+29 16	−35°R	10	10.90	5.07
Section Columns 5, 6, and 9 to 13 show Average Values	3	118.27—117.73	2888	11850		16.41	16.41	+ 0.18	−50°R	4	16.41	5.98
	4	117.73—117.18	2904	11750		16.50	16.50	+ 0.36	−50°R	4	16.50	5.86
	5	111.20 110.68	2768	23900		9.44	9.44	+18.70	−15°R	4	9.44	5.09
	6	101.46—101.01	2372	17350		14.45	12.82	+12.91	− 75°R	5	13.48	5.26
	7	96.30— 95.71	3100	4600		30.40	34.50	−28.45	+80°R	8	32.50	7.19
	8	91.14— 93.40	3924	3300		30.95	31.25	−11.70	+75°R	7	31.48	5.78
	9	90.51— 90.02	2572	5850		28.80	29.50	− 9.96	+70°R	6	29.25	5.64
	10	89.18— 88.72	2412	6200		27.75	26.95	1.97	+65°R	5	27.42	5.18
	11	83.72— 82.99	3856	7250		24.50	25.75	− 5.89	+25°R	6	25.03	4.80
	12	81.19 — 81.64	2348	6200		22.86	22.86	− 4.72	+35°R	4	22.86	4.95
	13	104.61—103.13	3884	14700		21.53	14.85	+17.00	+65°R	5	18.25	5.30
	14	109.85—109.10	3972	11600		15.17	23.90	−17.22	+70°R	1	19.30	6.47

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* For complete table heading see Table 36, p. 99.

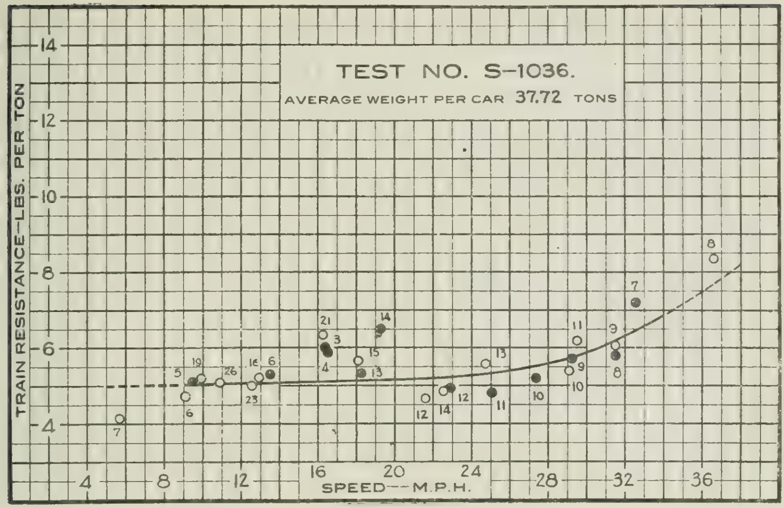
TEST NO. S-1036.
AVERAGE WEIGHT PER CAR 37.72 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36

FIG. 33

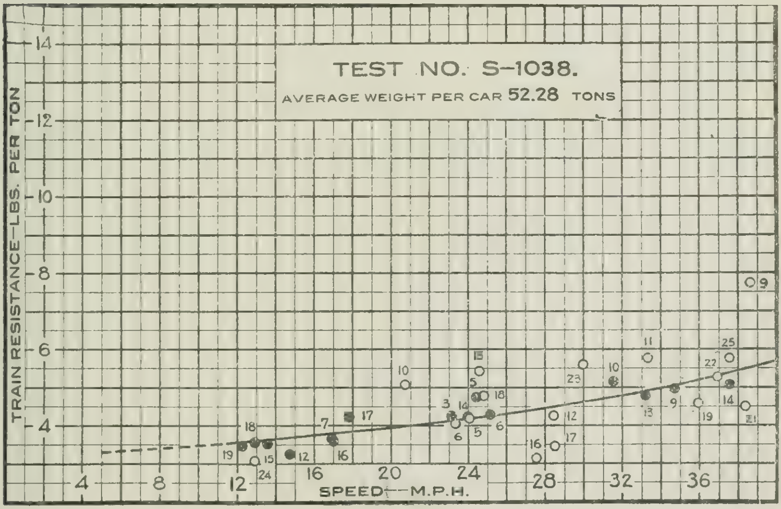
TEST NO. S-1038.
AVERAGE WEIGHT PER CAR 52.28 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36

FIG. 34

TABLE 51 TEST NO. S-1038*

From Champaign to Gilman, October 15, 1908. Weather: Fair. Temperature: 58 F. at start, 72° F. at end of test. Total weight behind measuring drawbar = 2144 tons, including the test car. Train length = 1650 ft. Center of mass 825 ft. back of measuring drawbar. 41 cars: 3 empty, 38 loaded. Kind of cars: 7 box, 32 gondola, 1 test, 1 caboose. Average weight per car = 52.28 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	5	117.32		9800	0			+0.96	+15°L	16	24.00	4.21
	6	115.84		10400	0			+2.08	+15°L	16	23.15	4.06
	7	113.84		14350	0			+8.01	+15°L	13	16.90	3.65
	9	106.00		5500	0			−13.60	+20°L	20	38.60	7.72
	10	100.53		13200	0			+2.85	+15°L	15	20.75	5.07
	11	99.29		8150	0			+5.18	+20°L	19	33.30	5.76
	12	93.18		8300	0			−0.96	+5°L	18	28.40	4.24
	14	89.55		10200	0			+1.41	+20°L	17	24.00	4.21
	15	88.74		10100	0			−1.85	+20°L	17	24.60	5.41
	16	87.71		9000	0			+2.78	+15°L	19	27.50	3.14
	17	87.04		8450	0			+1.28	+5°L	20	28.50	3.45
	18	86.42		10750	0			+0.64	+10°L	16	24.80	4.77
	19	97.86		6800	+0.0984			−28.15	+20°L	17	35.92	4.60
	21	97.54		3350	+0.0699			−24.95	+15°L	19	38.35	4.46
	22	97.76		6200	+0.0880			−28.15	+20°L	18	36.90	5.29
	23	98.90		9050	−0.0802			16.30	+25°L	16	29.95	5.57
	24	103.05		22800	−0.0370			+29.10	+5°L	9	12.85	3.09
	25	105.90		5500	0.			−8.42	+20°L	18	37.55	5.76
Section Columns 5, 6, and 9 to 13 show Average Values	3	117.06—118.18	5935	10000		23.65	24.15	+0.43	+15°L	16	23.12	4.23
	5	88.74—89.55	4260	10250		24.20	24.75	0.95	+20°L	17	24.20	4.71
	6	85.84—86.36	2768	10250		25.10	25.90	1.33	+10°L	16	25.15	4.28
	9	98.24—97.76	2544	7100		31.95	36.90	−28.65	+20°L	16	34.69	4.97
	10	99.29—98.90	2080	8100		32.80	29.95	+11.92	+20°L	17	31.51	5.14
	12	103.44—103.05	2050	19200		18.75	12.85	+31.70	+5°L	11	14.70	3.22
	13	105.18—104.58	3168	6850		35.10	30.60	+12.66	+15°L	17	33.20	4.78
	14	106.26—105.48	4120	6050		36.40	36.40	−5.92	+20°L	18	37.50	5.06
	15	111.10—110.65	2384	20150		14.75	13.55	+18.04	+20°L	11	13.53	3.54
	16	110.24—109.82	2236	17050		15.00	19.75	−1.89	+15°L	15	16.94	3.61
	17	114.74—114.24	2608	13750		18.70	17.80	+8.10	+15°L	13	17.80	4.22
	18	111.10—110.24	4536	20650		14.30	14.30	+15.95			12.85	3.59
	19	110.65—110.25	2152	21400		12.80	14.30	+13.73			12.22	3.48

* For complete table heading see Table 36, p. 99.

TABLE 52 TEST NO. S-1040

From Champaign to Gilman, October 24, 1908. Weather: Intermittent rain. Temperature: 57° F. at start, 53° F. at end of test. Total weight behind measuring drawbar = 2152 tons, including the test car. Train length = 1830 ft. Center of mass 900 ft. back of measuring drawbar. 47 cars: 2 empty, 45 loaded. Kind of cars: 21 box, 23 gondola, 1 tank, 1 test, 1 caboose. Average weight per car = 45.76 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	6	114.68		16500	0			+ 7.72	+40° R	8	10.77	4.75
	10	102.99		28100	0			+27.10	+20° R	8	3.82	2.92
	12	100.64		15100	0			+ 7.22	+35° R	10	12.45	4.28
	15	88.71		8900	0			1.53	+20° R	13	28.20	4.71
	16	86.32		9850	0			0.26	+15° R	11	24.82	4.67
	20	101.55		8900	0.0441			+ 9.53	+35° R	13	18.72	4.66
	23	100.85		13600	0.0194			+10.97	+30° R	10	13.25	3.99
	24	103.48		23000	0.0511			+30.00	+40° R	10	11.40	4.13
	25	108.45		13200	0.0255			+ 9.81	+35° R	11	17.05	4.82
Section Columns 5 and 9 to 13 show Average Values	9	90.52— 90.03	2584	8500		28.70	29.62	— 9.61	+25° R	13	29.36	6.14
	10	89.29— 88.52	3768	8750		28.80	28.20	1.64	+20° R	13	28.54	5.33
	11	86.32— 95.91	2180	10150		24.62	24.62	— 0.70	+15° R	11	24.77	4.98
	12	83.83— 83.16	3548	7000		26.70	27.10	4.99	+15° R	12	26.88	4.72
	13	93.64— 93.20	2200	4000		22.37	21.74	5.04	+26° R	12	23.10	4.64
	14	83.83— 83.00	4360	7250		26.70	27.80	5.82	+15° R	12	27.00	4.64
	15	106.10— 105.70	1988	7450		29.20	29.85	— 8.76	+25° R	13	30.10	5.45
	16	103.87— 104.64	4056	15100		22.75	16.70	+17.20	+20° R	9	19.75	4.56

* For complete table heading see Table 36, p. 99.

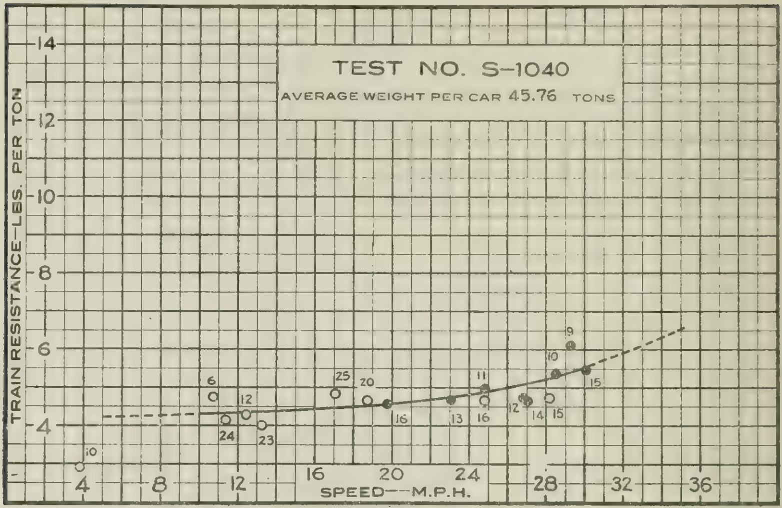
TEST NO. S–1040
AVERAGE WEIGHT PER CAR 45.76 TONS
TRAIN RESISTANCE–LBS. PER TON
SPEED––M.P.H.
4
6
8
10
12
14
4
8
12
16
20
24
28
32
36

FIG. 35

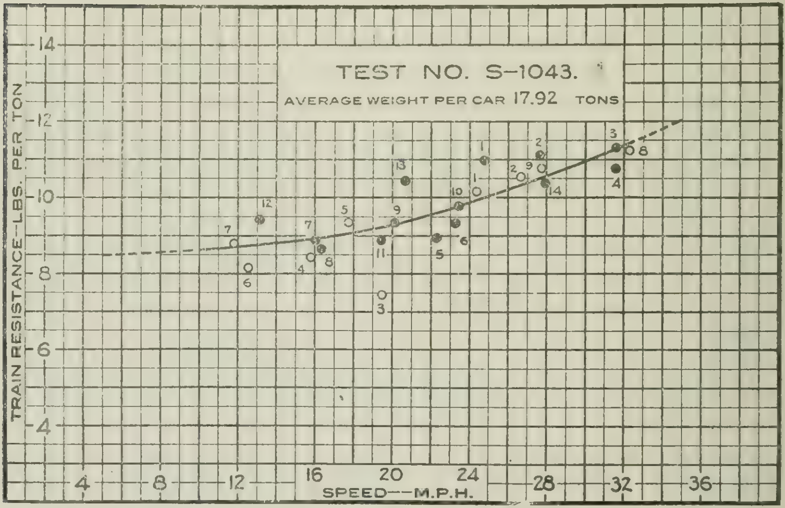
TEST NO. S–1043.
AVERAGE WEIGHT PER CAR 17.92 TONS
TRAIN RESISTANCE–LBS. PER TON
SPEED––M.P.H.
4
6
8
10
12
14
4
8
12
16
20
24
28
32
36

FIG. 36

TABLE 53 TEST NO. S-1043*

From Champaign to Mattoon, November 7, 1908. Weather: Clear. Temperature: 38° F. at start, 53° F. at end of test. Total weight behind measuring drawbar = 1118 tons, excluding the test car. Train length = 2580 ft. Center of mass 1300 ft. back of measuring drawbar. 66 cars: 65 empty, 1 loaded. Kind of cars: 15 box, 49 gondola, 1 tank, 1 caboose. Average weight per car = 16.92 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	1	142.05		11300	0			− 0.14	+25° R	8	24.35	10.15
	2	143.25		9400	+0.0124			− 8.80	+20° R	11	26.70	10.51
	3	150.77		11000	+0.0165			+ 2.00	+25° R	7	19.50	7.43
	4	156.10		13300	0			+ 9.21	+20° R	6	15.80	8.41
	5	157.78		11700	0			+ 2.97	+ 5° R	7	17.75	9.33
	6	168.23		15100	0			+14.13	+65° R	4	12.55	8.14
	7	168.78		17000	+0.0106			+14.21	+55° R	4	11.80	8.76
	8	147.29		7400	0			−12.11	+15° R	13	32.30	11.21
	9	143.90		8650	0			− 7.96	+10° R	11	27.75	10.75
Section Columns 5 and 9 to 13 show Average Values	1	139.25—140.49	6540	10500		24.70	25.50	− 3.97	+30° R	8	24.76	10.97
	2	143.70—144.40	3652	8800		27.96	26.87	− 5.12	+15° R	11	27.67	11.01
	3	146.20—147.52	6960	7500		29.43	32.10	−16.61	+ 5° R	13	31.60	11.29
	4	147.52—148.31	4172	7600		32.10	30.42	− 5.50	+ 5° R	13	31.60	10.72
	5	151.00—152.47	7832	11100		20.00	22.50	− 0.03	+15° R	9	22.25	8.93
	6	152.47—153.45	5112	9150		22.50	23.90	− 4.70	+25° R	10	23.24	9.31
	7	155.27—156.20	4952	13350		16.33	15.75	+ 9.02	+20° R	6	16.07	8.79
	8	156.20—157.16	5028	13850		15.75	17.00	+ 8.34	+20° R	6	16.32	8.63
	9	159.65—166.66	5316	10620		18.60	22.75	− 5.94	+15° R	8	20.13	9.41
	10	160.66—162.22	8248	8500		22.75	20.90	− 3.84	+15° R	8	23.43	9.76
	11	165.74—166.74	5276	11600		20.25	18.02	+ 7.04	+50° R	7	19.45	8.88
	12	168.43—169.53	5792	15400		12.40	16.27	+ 8.20	+55° R	4	13.16	9.40
	13	169.53—170.72	6272	11400		16.27	22.15	− 7.87	+15° R	9	20.70	10.41
	14	145.58—146.20	3276	9150		26.90	29.40	−13.96	+ 5° R	11	27.94	10.35

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* For complete table heading see Table 36, p. 99.

TABLE 54 TEST NO. S-1048*

From Champaign to Ludlow, November 28, 1908. Weather: Fair. Temperature: 36° F. at start, 39° F. at end of test. Total weight behind measuring drawbar = (a)-2443 tons, (b)-2355 tons, including the test car. Train length = (a)-2175 ft. (b)-2100 ft. Center of mass 925 ft. back of measuring drawbar (a)-54 cars, (b)-52 cars, 8 empty, (a)-46 loaded. (b)-44 loaded. Kind of cars: 18 box (a)-34 gondola, (b)-32 gondola, 1 test, 1 caboose. Average weight per car = 45 24 tons. (a)—Champaign to Rantoul. (b)—Rantoul to Ludlow.

1	2	3	4	5	6	7	8	6	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	1	110.74		26750	0			+18.86	+ 5° L	5	9.35	4.21
	2	111.17		30150	0			+24.13	+ 5° L	5	7.78	3.65
	3	114.44		18200	0			+ 8.26	+25° L	6	14 00	4.33
	4	115.79		14200	0			+ 1.91	+30° L	6	18 36	5.08
	5	116.48		13550	0			+ 0.73	+25° L	7	19.36	5.27
	6	117.61		12800	0			0	+30° L	5	19.45	5.24
	7	118 43		13550	0			— 0.49	+ 5° L	6	19.73	5.74
	10	115.34		14800	—0.0229			+ 7.28	+30° L	6	17.36	5.46
	11	114.71		17800	—0.0053			+ 9.47	+25° L	6	14.27	4.20
	14	110.53		29350	0			+20.10	+ 5° L	5	8.73	4.84
	15	110.16		20950	+0.0388			+ 0.25	+10° L	6	11.73	5.16
	16	111.01		29850	+0.0123			+20.10	+ 5° L	5	8.28	3.89
	17	111.80		17800	—0.0900			+28.15	+15° L	5	16.45	5.37
	18	111.59		21950	0 0652			+29.91	+15° L	5	12.00	4.15
	19	111.40		28550	—0.0352			+29.16	+15° L	5	9.10	4.39
	20	109.83		17400	+0.0405			— 4.78	+10° L	8	15.00	5.38
	21	111.51		25500	0.0511			+29.91	+15° L	5	10.64	4.31
	22	109.09		9900	+0.0476			—19.35	+ 0°	9	24.20	7.05
	23	108.69		11000	—0 0405			+ 6.54	+ 5° R	9	23.91	6.01
	24	108.31		12200	0.0493			+10.30	+ 5° R	9	21.30	5.92
	25	108.49		11200	—0.0511			+ 9.05	+ 5° R	9	23.00	6.15
Section Columns 5 and 9 to 13 show Average Values	5	118.42—117.61	4306	13400		19.73	19.45	0	+30° L	5	19.58	5.66
	6	115.94—115.34	3172	14650		18.27	17.36	+ 4.49	+30° L	6	18.02	5.00
	7	114.71—114.24	2476	18100		11.27	13.82	+ 8.11	+25° L	6	14.06	4.69
	9	111.40—110.61	4176	29000		9.10	9.10	+21.40	+ 5° L	5	8.50	4.19
	10	108.69—108.31	2008	11000		23.90	21 30	+ 9.21	+ 5° L	9	22.80	5.20
	11	112.06—111.40	3488	20000		20.82	9.10	+28.30	+15° L	5	13.98	4.72

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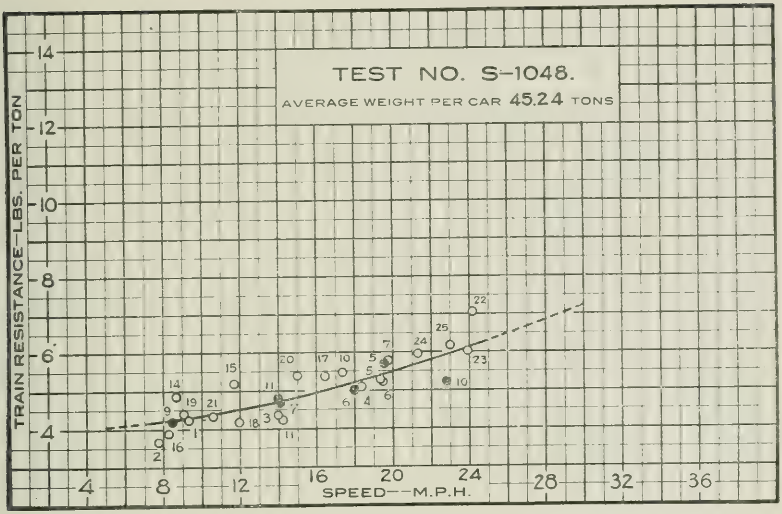
* For complete table heading see Table 36, p. 99.


TEST NO. S-1048.
AVERAGE WEIGHT PER CAR 45.24 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36
22
25
24
23
7
5
5
10
6
4
6
17
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3
7
11
18
14
19
21
9
1
16
2

Fig. 37

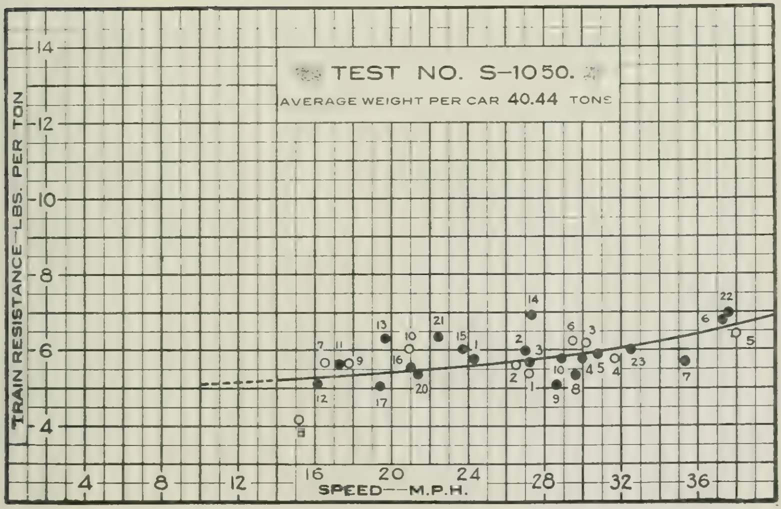
TEST NO. S-1050.
AVERAGE WEIGHT PER CAR 40.44 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36
22
6
5
14
6
3
13
21
15
1
2
3
7
11
9
10
16
20
12
17
2
1
10
9
8
4
5
4
23
7

Fig. 38

TABLE 55 TEST NO. S-1050*

From Champaign to Mattoon, January 23, 1909. Weather: Fair. Temperature: 53° F. at start, 66° F. at end of test. Total weight behind measuring drawbar = 1618 tons, excluding the test car. Train length = 1620 ft. Center of mass 660 ft. back of measuring drawbar. 40 cars: 16 empty, 24 loaded. Kind of cars: 29 box, 10 gondola, 1 caboose. Average weight per car = 40.44 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary values	1	141.33		7800	0			— 1.50	+ 0°	4	27.20	5.39
	2	142.12		7900	0			— 1 83	+ 11° R	5	26.55	5.57
	3	144.65		7500	0			— 4.04	+ 0°	7	30.20	6.17
	4	145.56		6050	0			— 5.25	+ 0°	6	31.70	5.73
	5	147.33		4550	0			— 9.46	+ 0°	6	38.00	6.40
	6	153.18		5900	0			6.81	+65° R	6	29.46	6.23
	7	155.97		14900	0			+ 9.32	—60° R	8	16.55	5 68
	8	157.87		7250	0			+ 0.88	—45° R	6	15.18	4.15
	9	156.97		14100	0			+ 8.15	— 60° R	11	17.77	5.62
	10	158.87		10400	0			+ 1.08	— 60° R	14	20.95	6.02
Section Colums 5 and 9 to 13 show Average Values	1	139.00—140.21	6420	9100		23.14	25.72	— 3.91	+40° R	3	24.31	5.75
	2	140.21—141.56	7116	8200		25.72	27.50	— 4.82	+ 0°	4	26.95	5.97
	3	141.56—142.93	7188	7800		27.50	29.10	— 4.55	+10° R	5	27.23	5 67
	4	142.93—143.80	4616	7100		29.00	31.22	— 8.92	+ 0°	7	30.00	5.76
	5	143.80—145.16	7220	6950		31.22	31.20	— 4.17	+ 0°	7	30.78	5.89
	6	146.25—147.49	6560	4950		35.30	37.90	15 13	+ 0°	6	37.30	6.79
	7	148.22—148.91	3632	4950		36.25	33 82	+ 1.67	+15° R	6	35.36	5.68
	8	150.79—151.78	5216	6950		30.20	29 10	— 0.40	+35° R	4	29.63	5.32
	9	151.78—152.57	4196	7400		29.10	28.55	+ 0.06	+60° R	5	28.60	5.08
	10	152.57—153.18	3176	7500		28.55	29.46	— 5.94	+65° R	6	28.87	5 74
	11	156.11—156.97	4552	14800		16.90	17.77	+ 8.15	—60° R	11	17.25	5.60
	12	157.48—158.25	4016	8850		17.23	17.23	+ 1.01	—45° R	6	16.11	5.09
	13	159.30—159.87	3032	13550		19.77	19 77	+ 5.48	—60° R	14	19.70	6.29
	14	160.80—161.79	5212	7750		26.64	26.64	— 5.68	—60° R	14	27.35	6.94
	15	162.59—163.28	3644	9200		22.90	21.37	— 4.35	—55° R	12	23.66	6.01
	16	164.96—165.66	3696	10550		20.37	21.73	— 0.16	—30° R	9	21.00	5.51
	17	166.19—166.84	3412	11800		20.55	18.60	+10.13	—25° R	8	19.40	5.01
	20	165.66—166.19	2828	10000		21.73	20.55	+ 5.45	—30° R	7	21.41	5 34
	21	159 87—160.62	3956	10400		19.77	25.55	—11.88	—60° R	13	22.46	6 34
	22	147.49—148.22	3860	4700		37.80	36.25	— 5.27	+10° R	7	37.60	6.96
	23	145.16—146.25	5716	6600		31.20	35.30	—13.76	+ 0°	6	32.50	5.99

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* For complete table heading see Table 36, p. 99.

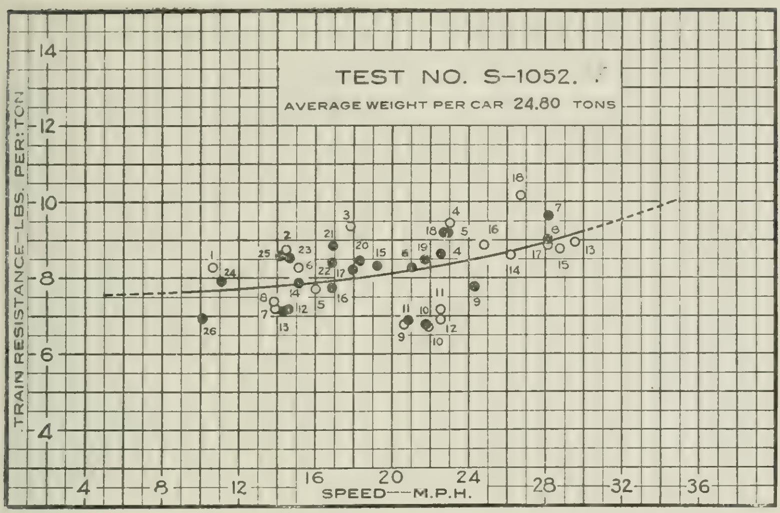
TEST NO. S–1052.
AVERAGE WEIGHT PER CAR 24.80 TONS
TRAIN RESISTANCE–LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36

FIG. 39

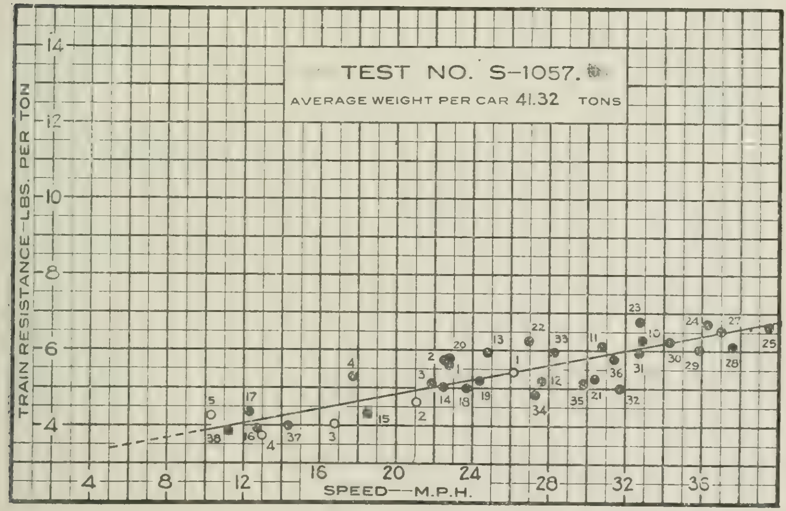
TEST NO. S–1057.
AVERAGE WEIGHT PER CAR 41.32 TONS
TRAIN RESISTANCE–LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36

FIG. 40

TABLE 56 TEST NO. S-1052

From Champaign to Mattoon, January 28, 1909. Weather: Continuous rain. Temperature: 36° F. at start, 40° F. at end of test. Total weight behind measuring drawbar = 1514 tons, excluding the test car. Train length = 2430 ft. Center of mass 1316 ft. back of measuring drawbar. 61 cars: 44 empty, 17 loaded. Kind of cars: 36 box, 23 gondola, 1 flat, 1 caboose. Average weight per car = 24.80 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method of Calculation	Item No.	Location on Road	Length of Section feet	Total Drawbar Pull pounds	Acceleration Miles per hour per second	Speeds		Grade + Up − Down feet per mile	Wind		Speed m. p. h.	Net Train Resistance pounds per ton
		Milepost No.				At Entrance to Section m. p. h.	At Exit from Section m. p. h.		Approximate Direction	Approximate Velocity m. p. h.		
				P	A	V_1	V_2	G			V	R
Point Columns 5, 6, and 9 to 13 show Momentary Values	1	168.75		20850	0			+14.52	-45° L	14	10.64	8.27
	2	167.12		16050	0			+ 4.99	−50° L	19	14.45	8.71
	3	165.72		14400	0			+ 0.43	60° L	18	17.82	9.35
	4	161.23		9550	0			− 8.25	−70° L	12	23.00	9.43
	5	159.84		13800	0			+ 3.75	50° L	14	16.00	7.70
	6	157.37		16750	0			+ 7.38	55° L	10	15.10	8.26
	7	155.97		16400	0			+ 9.66	50° L	11	13.90	7.18
	8	155.11		15800	0			+ 8.10	50° L	11	13.86	7,37
	9	152.52		9900	0			− 0.54	−80° L	6	20.64	6.75
	10	151.34		9750	0			− 0.65	90° L	7	21.90	6.69
	11	153.50		8650	0			− 3.77	−85° L	6	22.55	7.15
	12	149.60		9550	0			− 1.52	+70° L	6	22.46	6.89
	13	147.20		5800	0			−13.44	+85° L	10	29.47	8.92
	14	148.29		6900	−0 0388			− 0.74	+85° L	8	26.20	8.60
	15	147.44		5800	−0.0166			− 8.73	90° L	9	28.80	8,75
	16	148.57		9200	−0.0352			+ 1.71	+80° L	7	24.82	8.84
	17	146.59		8500	+0.0401			−18.85	+85° L	10	28.10	8.87
	18	146.33		8900	+0.0453			−22.88	+85° L	11	26.73	10.17

Section Columns 5, and 9 to 13 show Average Values	4	142.87—143.62	3972	9600		21.64	23.15	9.18	80° L	10	22.55	8.61
	5	143.62—144.38	4032	8850		23.15	21.64	5.70	—65° L	13	22.92	9.19
	6	144.38—145.20	4312	10000		21.64	21.55	— 4.14	—66° L	10	21.00	8.24
	7	146.22—147.15	4956	8000		25.91	29.29	—18.46	+85° L	10	28.16	9.61
	8	147.15—148.29	5980	6200		29.29	26.20	— 7.56	90° L	9	28.13	9.00
	9	148.29—149.09	4268	8450		26.20	23.00	+ 1.17	+80° L	7	24.26	7.76
	10	151.12—151.85	3828	9400		22.10	21.28	— 0.28	90° L	7	21.74	6.77
	11	151.85—152.55	3676	9800		21.28	20.64	+ 0.32	80° L	6	20.90	6.88
	12	156.01—156.74	3840	16850		14.10	15.00	+ 9.22	—54° L	11	14.54	7.16
	13	155.29—156.01	3780	16000		14.18	14.10	+ 9.22	—50° L	11	14.31	7.12
	14	156.74—157.37	3332	16100		15.00	15.10	+ 7.29	—55° L	10	15.15	7.82
	15	158.23—159.24	5314	11200		18.00	18.00	2.37	—55° L	12	19.20	8.30
	16	159.24—159.80	2964	13300		18.00	15.90	+ 7.31	—45° L	13	16.84	7.73
	17	159.80—160.69	4732	12500		15.90	21.36	— 7.92	50° L	14	17.92	8.21
	18	160.69—161.45	3996	9600		21.36	22.82	10.47	—70° L	12	22.70	9.16
	19	161.45—162.17	3816	9550		22.82	18.91	+ 2.31	—60° L	14	21.68	8.46
	20	162.17—163.08	4828	13400		18.91	19.50	+ 0.23	—55° L	13	18.29	8.41
	21	164.85—165.69	4460	15200		15.82	17.82	+ 0.35	60° L	18	16.90	8.84
	22	165.69—166.67	5172	14600		17.82	15.18	+ 6.48	—60° L	16	16.80	8.39
	23	166.67—167.26	3116	16100		15.18	13.86	+ 7.88	50° L	19	14.66	8.52
	24	168.57—169.13	2928	20400		10.91	12.64	+12.10	—45° L	14	11.09	7.90
	25	169.13—169.60	2492	17000		12.64	15.40	+ 1.25	—50° L	13	14.15	8.56
	26	171.44—171.72	1484	22600		12.32	8.50	+31.20	50° L	14	10.12	6.91

TABLE 57 TEST NO. S-1057

From Champaign to Gilman, March 6, 1909. Weather: Fair. Temperature: 34° F. at start, 40° F. at end of test. Total weight behind measuring drawbar = 2107 tons, including the test car. Train length = 1830 ft. Center of mass 860 ft. back of measuring drawbar. 51 cars: 8 empty, 43 loaded. Kind of cars: 23 box, 22 gondola, 3 flat, 1 tank, 1 test, 1 caboose. Average weight per car = 41.32 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method of Calculation	Item No.	Location on Road Milepost No.	Length of Section feet	Total Drawbar Pull pounds	Acceleration miles per hour per second	Speeds At Entrance to Section m. p. h.	Speeds At Exit from Section m. p. h.	Grade + Up − Down feet per mile	Wind Approximate Direction	Wind Approximate Velocity m. p. h.	Speed m. p. h.	Net Train Resistance pounds per ton
				P	*A*	V_1	V_2	*G*			*V*	*R*
Point Columns 5, 6, and 9 to 13 show Momentary Values	1	104.55		13600	−0.0561			+16.76	+10°L	8	26.16	5.41
	2	103.87		16800	−0.0723			+26.88	+ 5°L	13	21.02	4.63
	3	103.57		19550	−0.0638			+29.78	"	13	16.80	4.04
	4	103.29		24950	−0.0440			+32.38	"	13	13.00	3.73
	5	102.93		28350	0			+24.28	+10°L	6	10.32	4.26

Section Columns 5 and 9 to 13 show Average Values	1	117.91—117.18	4004	12800		22.57	23.05	+ 0.20	+20° R	6	22.75	5.62
	2	117.18—115.94	6596	13150		23.05	22.16	+ 2.41	+15° R	7	22.50	5.75
	3	115.91—115.36	3044	12950		22.16	21.42	+ 4.58	+20° R	6	21.85	5.14
	4	114.69—114.22	2472	17000		18.20	17.98	+ 7.90	+15° R	6	17.75	5.30
	10	106.08—105.53	2892	9150		32.35	32.08	— 4.02	+10° L	7	32 86	6.28
	11	105.53—105.02	2704	10050		32.08	29.20	+ 8.40	+10° L	8	30.74	6.11
	12	105.02—104.56	2428	11950		29.20	26.16	+13.92	+10° L	8	27.60	5.20
	13	104.56—104.25	1636	11600		26.16	24.10	+14.20	+10° L	8	24.79	5.93
	14	101.25—103.87	1976	15700		24.10	21.02	+19 24	+ 5° L	13	22.45	5.03
	15	103.87—103.57	1621	18350		21.02	16.80	+29.60	+ 5° L	13	18.45	4.32
	16	103.57—103.05	2701	24000		16.80	10.58	+31.25	+ 5° L	13	12.72	3.92
	17	103 05—102.40	3436	24000		10.58	18.88	+ 5.53	+10° L	6	12.33	4.37
	18	102.40—101.65	3988	12800		18.88	25.76	11.25	+25° L	9	23.65	5.00
	19	101.65—101.24	2144	12800		25.76	23.50	+11.82	+25° L	9	24.38	5.20
	20	101.24— 99.79	7680	13500		23.50	28.72	— 4.88	+25° L	8	22.77	5.80
	21	99.79— 98.95	4452	6950		28.72	28.25	— 4.03	+25° L	8	30.38	5.25
	22	98 95— 98.05	4744	8100		28.25	30.32	—11.02	+20° L	9	26.95	6.26
	23	98.05— 97.50	2884	5800		30.32	34.54	—28.02	—35° L	11	32.76	6.78
	24	97.50— 96.05	7704	5400		34.70	37.55	—15.83	—35° L	11	36.24	6.71
	25	96.05— 95.38	3476	4950		37.55	41.10	—25.98	+35° L	12	39.50	6.64
	26	95.38— 94.60	4144	4450		41.10	37.90	1.02	+35° L	12	40.38	6.73
	27	94.60— 93.93	3528	6600		37.90	37.25	6.44	+35° L	12	37.00	6.53
	28	93.93— 93.31	3308	6100		37.25	37.25	— 8.46	+35° L	12	37.60	6.11
	29	90.09— 89.50	3156	5900		36.21	35.25	— 4.52	+35° L	11	35.86	6.02
	30	89.50— 88.92	3016	6900		35.25	33.55	— 0.70	+35° L	11	34.28	6.23
	31	88.92— 88.02	4792	7550		33.55	32.45	— 3.42	+35° L	11	32.68	5.93
	32	88.02— 86.79	3500	7600		32.45	30.62	— 0.41	+35° L	7	31.66	4.99
	33	86.79— 86.20	3108	8850		30.62	27.60	+ 5.78	+40° L	9	28.25	5.93
	34	86.20— 85.74	2396	9250		27.60	27.80	— 1.98	+40° L	9	27.23	4.82
	35	83.88 — 83.38	2616	9800		29.21	30.02	— 4.64	+40° L	9	29.75	5.14
	36	83.38— 82.16	6444	8750		30.02	31.40	— 6.72	+40° L	9	31.40	5.79
	37	103.57—103.29	1472	22100		16.80	13.00	+31.20	+ 5° L	13	14.34	4.00
	38	103.29—103.05	1232	26400		13.00	10.58	+31.30	+ 5° L	13	11.20	3.88

TABLE 58 TEST No.S-1061*

From Champaign to Gilman, March 13, 1909. Weather: Fair. Temperature: 41° F. at start, 38° F. at end of test. Total weight behind measuring drawbar = 2252 tons, including the test car. Train length = 1785 ft. Center of mass 850 ft. back of measuring drawbar. 44 cars: 3 empty, 41 loaded. Kind of cars: 37 Gondola, 5 flat, 1 test, 1 caboose. Average weight per car = 51.20 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5. and 9 to 13 show Average Values	1	117.14—115.91	6496	11550		18.20	16.41	+ 2.40	+70° L	5	17.05	4.87
	2	115.91—115.34	3000	12000		16.41	14.95	+ 5.02	+70° L	5	15.73	4.48
	3	111.66—110.96	3724	21900		18.13	10.25	+25.70	90° L	5	12.10	4.10
	4	110.96—109.84	5888	22400		10.25	17.05	+ 9.43	+75° L	10	11.47	4.21
	5	109.84—109.22	3304	14000		17.05	25.00	−17.44	−85° L	7	20.50	5.87
	6	109.22—108.31	4792	9850		25.00	23.00	− 0.33	+75° L	6	25.15	5.88
	7	106.86—106.12	3904	7850		29.81	32.20	−14.50	+70° L	7	31.30	6.38
	8	106.12—105.58	2872	7150		32.20	31.91	− 5.70	+70° L	7	32.65	5.79
	9	105.58—104.96	3304	9250		31.91	28.20	+ 7.90	+65° L	7	30.00	5.77
	10	104.96—104.26	3676	12100		28.20	22.57	+14.75	+85° L	7	25.05	5.13
	11	104.26—103.65	3224	17150		22.57	15.49	+21.90	+60° L	7	19.10	5.06
	12	103.65—103.31	1800	22450		15.49	9.70	+30.00	+80° L	9	12.27	4.15
	13	103.31—103.04	1464	27050		9.70	5.15	+31.00	+65° L	4	6.88	3.43
	14	103.31—103.18	720	26200		9.70	7.37	+32.30	+65° L	4	8.18	3.18
	15	103.18—103.04	744	28000		7.37	5.15	+29.90	+65° L	4	5.90	3.67
	16	98.14— 97.61	2776	7650		24.23	29.57	−27.40	+65° L	8	27.03	6.67
	17	97.61— 95.76	9800	6000		29.57	36.17	−18.75	+60° L	8	32.60	6.73
	18	95.76— 95.29	2472	4450		36.10	37.68	−23.50	+50° L	10	37.40	7.64
	19	95.29— 94.58	3772	4450		37.68	34.10	+ 2.03	+50° L	10	36.75	5.91
	20	94.58— 93.79	4136	5600		34.09	33.60	− 7.68	+45° L	10	33.16	5.95
	21	93.79— 93.24	2956	5200		33.60	32.91	− 7.15	+45° L	10	33.55	6.09
	22	86.71— 85.77	4960	11000		20.06	19.10	+ 1.28	90° L	9	19.00	4.91
	23	83.67— 82.97	3728	8250		22.70	24.03	− 6.00	+60° L	7	23.10	4.78
	25	81.65— 81.30	1868	8300		16.98	17.52	− 5.10	+80° L	8	16.97	4.93

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* For complete table heading see Table 36. p. 99.

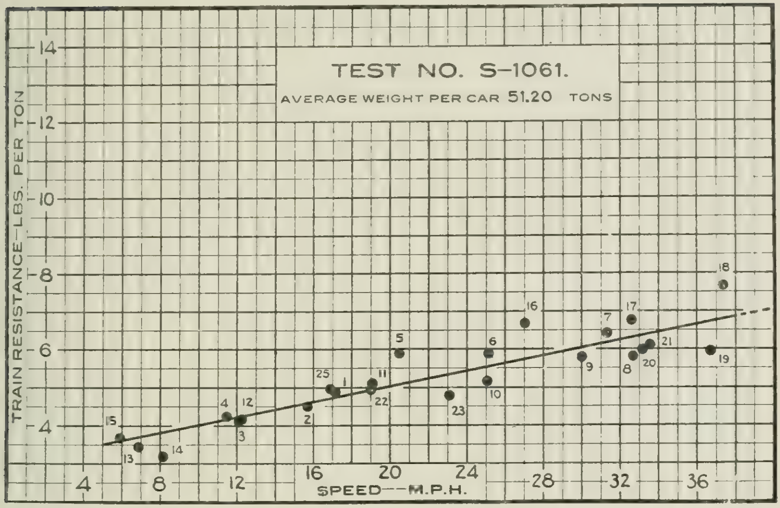
TEST NO. S–1061.
AVERAGE WEIGHT PER CAR 51.20 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36
15
13
14
4
12
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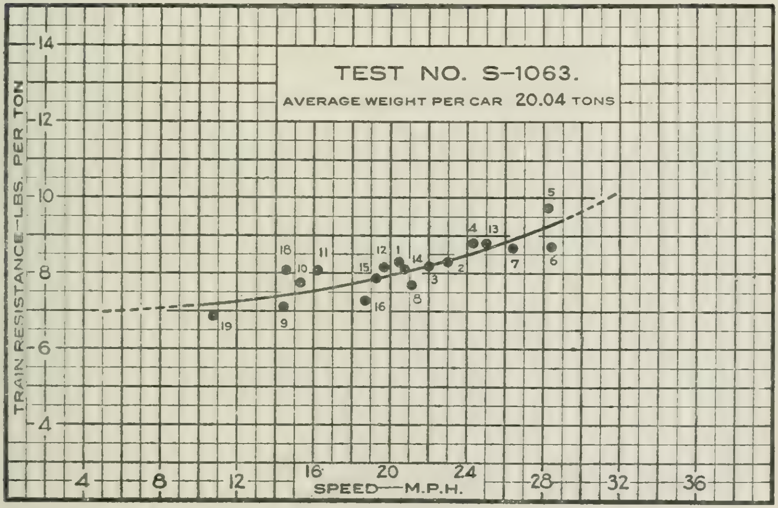
FIG. 41


TEST NO. S–1063.
AVERAGE WEIGHT PER CAR 20.04 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36
19
9
18
10
11
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1
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FIG. 42

TABLE 59 TEST NO. S-1063*

From Champaign to Mattoon, March 19, 1909. Weather: Intermittent rain. Temperature: 39° F. at start, 40° F. at end of test. Total weight behind measuring drawbar = 1484 tons, excluding the test car. Train length = 3060 ft. Center of mass 1200 ft. back of measuring drawbar. 74 cars: 70 empty, 4 loaded. Kind of cars: 4 box, 69 gondola, 1 caboose. Average weight per car = 20.04 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 show Average Values	1	141.71—142.84	6000	10800		20.74	21.61	− 3.74	+35° R	13	20.45	8.26
	2	143.53—144.45	4900	8450		22.91	22.10	− 5.40	+35° R	14	23.00	8.29
	3	144.45—145.34	4672	9800		22.10	22.71	− 5.20	+35° R	14	22.00	8.15
	4	145.34—146.42	5700	8850		22.71	27.21	−14.90	+40° R	15	24.30	8.77
	5	146.42—147.20	4144	6900		27.21	28.61	−16.95	+40° R	15	28.25	9.70
	6	147.20—147.83	3336	6700		28.61	28.00	− 9.01	+40° R	15	28.40	8.69
	7	147.83—148.60	4064	7200		28.00	21.91	− 2.34	+40° R	15	26.40	8.64
	8	152.50—153.52	5416	10100		20.35	22.14	− 4.90	+30° R	13	21.10	7.66
	9	155.78—156.82	5484	16050		14.30	15.10	+ 8.95	+20° R	10	14.40	7.10
	10	156.82—157.37	2912	16000		15.10	15.24	+ 7.80	+20° R	10	15.30	7.71
	11	157.37—158.16	4156	15600		15.24	17.73	+ 2.80	+30° R	10	16.20	8.03
	12	158.16—159.35	6336	12450		17.73	19.09	− 0.84	+30° R	10	19.65	8.14
	13	161.21—161.48	1472	9200		25.00	25.10	− 7.50	+30° R	13	25.00	8.79
	14	162.17—163.12	5028	12000		21.69	21.61	+ 0.10	+30° R	12	20.75	8.09
	15	165 07—165.77	3720	13200		18.11	19 61	− 0.14	+35° R	12	19.25	7.85
	16	165.77—166.85	5680	13050		19.60	16.56	+ 7.80	+35° R	12	18.70	7.24
	18	169.38—169.66	1492	14950		13.95	14.93	+ 1.77	+40° R	9	14.55	8.08
	19	171.55—171.71	870	22200		11.96	9.86	+31.50	+25° R	8	10.78	6.84

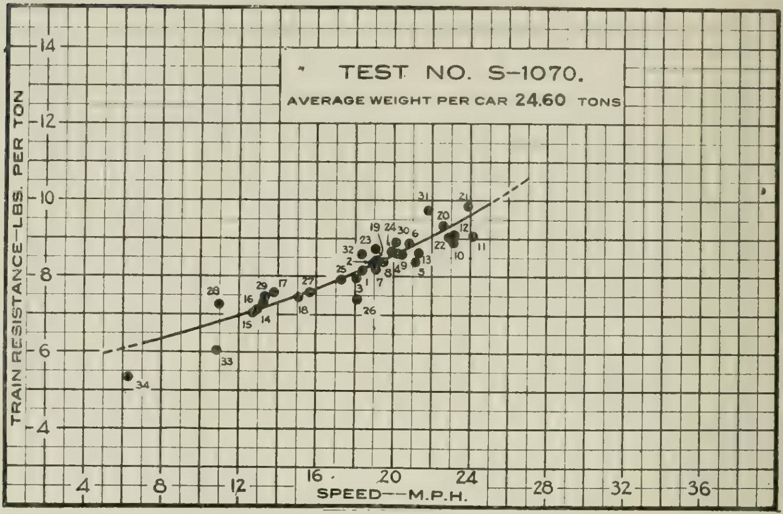
* For complete table heading see Table 36, p. 99.

TABLE 60 TEST NO. S–1070

From Champaign to Mattoon, April 17, 1909. Weather: Fair. Temperature: 58° F. at start, 71° F. at end of test. Total weight behind measuring drawbar = 1622 tons, including the test car. Train length = 2400 ft. Center of mass 1091 ft. back of measuring drawbar. 66 cars: 49 empty, 17 loaded. Kind of cars: 21 box, 28 gondola, 15 stock, 1 test, 1 caboose. Average weight per car = 24.60 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 show Average Values	1	140.20—140.89	3636	11150		17.90	19.53	— 6.55	+ 0°	1	18.35	8.16
	2	140.89—141.70	4304	10800		19.53	18.65	— 2.94	+ 0°	1	18.90	8.31
	3	141.70—142.70	5308	11850		18.65	19.61	— 2.98	+ 0°	1	18.10	7.94
	4	142.70—143.38	3572	10150		19.61	21.19	— 9.47	+ 0°	1	20.25	8.57
	5	143.38—143.79	2164	9200		21.19	21.75	— 9.25	+ 0°	1	21.10	8.38
	6	143.79—144.37	3056	9150		21.75	20.13	— 4.33	+ 0°	1	20.80	8.86
	7	144.37—145.03	3496	10400		20.13	19.40	— 3.32	+ 0°	1	19.05	8.26
	8	145.03—145.38	1856	9900		19.40	19.98	— 8.26	+ 0°	1	19.45	8.36
	9	145.38—146.15	4040	9050		19.98	22 57	—13.00	+ 0°	1	20.40	8.57
	10	146.15—146.47	1692	5000		22.57	23.97	—22.50	+ 0°	1	23.10	8.88
	11	146.47—147.21	3892	5650		23.97	24.71	—16.40	+ 0°	1	24.10	9.04
	12	147.21—147.82	3236	5800		24.71	22.70	— 9.00	+ 0°	1	23.20	9.08
	13	147.82—148.32	2660	7700		22.70	20.61	— 3.77	+ 0°	1	21.30	8 60
	14	155.43—155.95	2740	16800		13.52	12.85	+ 9.80	+60° L	7	12.90	7.10
	15	155.94—156.41	2432	17500		12.85	13.10	+ 9 35	+60° L	7	12.75	7.06
	16	156.41—156.87	2124	17750		13.10	13 96	+ 7.83	+60° L	7	13.21	7.30
	17	156.87—157.36	2632	17600		13.96	14.30	+ 8.04	+60° L	7	13.80	7.54
	18	157.36—158.10	3864	16600		14.30	17.12	+ 3.14	+60° L	4	15.05	7.42
	19	158.10—159.29	6284	13950		17.12	18.87	— 1.35	+60° L	4	19.05	8.40
	20	160.55—160.80	1324	12650		21.90	23.63	—15.20	75° L	3	22.60	9.32
	21	160.80—161.36	2980	11600		23.63	24.45	— 9.57	—75° L	3	23.90	9.84
	22	161.36—162.19	4368	11300		24.45	20.43	+ 2.30	—75° L	3	22.90	9.02
	23	162.19—162.77	3072	14100		20.43	19.53	+ 2.15	—75° L	3	19.02	8.70
	24	162.77—163.16	2040	13400		19 53	20.43	— 4.27	— 75° L	3	19.90	8.63
	25	164.94—165.73	4188	14700		16.30	18.40	— 0 19	90° L	9	17.30	7.90
	26	165 73—166.16	2248	13600		18.40	17.74	+ 4.70	90° L	9	18.05	7.36
	27	166.16—166.85	3660	15050		17.74	14.62	+ 9.72	90° L	9	15.60	7.56
	28	168.36—168.69	1692	20750		11.40	10.98	+15.60	90° L	12	11.00	7.28
	29	168.69—169.63	4984	18650		10.98	16.45	+ 5.10	90° L	12	13.32	7.43
	30	169.63—170.56	4876	13600		16.45	22.70	—10.70	—65° L	6	20.10	8.87
	31	170.56—170.83	1440	12700		22.70	21.77	+ 0.37	— 65° L	6	21.80	9.73
	32	170.83—171.42	3084	13550		21.77	14.30	+15.75	—65° L	6	18.30	8.58
	33	171.42—171.75	1752	20950		14.30	8.75	+31.90	+80° L	4	10.85	6.02
	34	171.86—172.10	1308	27050		7.60	6.00	+33.10	+80° L	4	6.38	5.32

r complete table heading see Table 36, p. 99.


TEST NO. S-1070.
AVERAGE WEIGHT PER CAR 24.60 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED——M.P.H.
4
8
12
16
20
24
28
32
36
31
21
20
12
19
24
30
6
23
22
10
11
32
13
2
9
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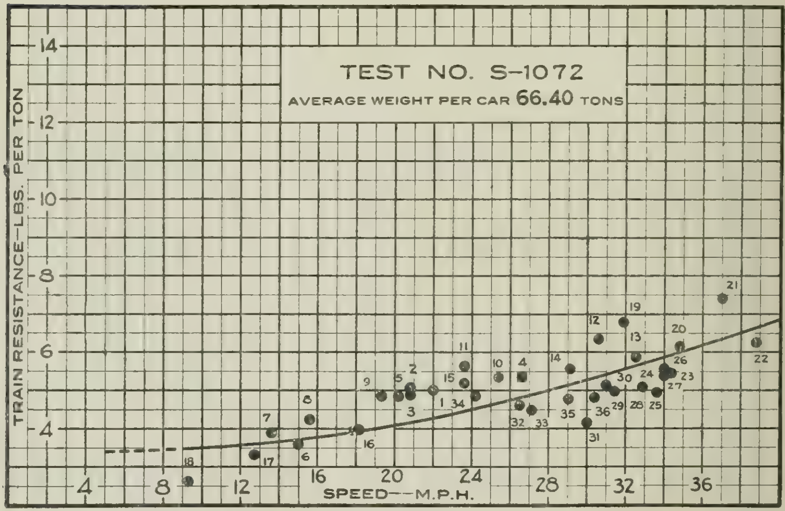
34

FIG. 43


TEST NO. S-1072
AVERAGE WEIGHT PER CAR 66.40 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED——M.P.H.
4
8
12
16
20
24
28
32
36
21
19
12
20
22
13
26
11
10
4
14
2
5
15
30
24
23
27
9
3
1
34
35
36
29
28
25
32
33
31
7
8
16
6
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18

FIG. 44

TABLE 61 TEST NO. S-1072*

From Champaign to Gilman, May 1, 1909. Weather: Fair. Temperature: 35° F. at start, 37° F. at end of test. Total weight behind measuring drawbar = 1859 tons, excluding the test car. Train length = 1200 ft. Center of mass 600 ft. back of measuring drawbar. 28 cars: 1 empty, 27 loaded. Kind of cars: 27 gondola, 1 caboose. Average weight per car = 66.40 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 show Average Values	1	118.31—117.62	3156	8600		22.30	21.82	+ 0.15	+75° L	22	22.00	4.98
	2	117.62—116.09	8212	10000		21.82	20.27	+ 2.25	+75° L	22	20.80	5.07
	3	116.09—115.37	3816	12350		20.27	20.75	+ 3.74	+75° L	22	20.80	4.88
	4	112.20—111.87	1752	11750		28.85	24.78	+25.00	90° L	21	26.60	5.34
	5	111.87—111.36	2668	14100		24.78	16.80	+29.70	90° L	21	20.20	4.83
	6	111.36—110.80	2968	17800		16.80	14.55	+20.11	+80° L	19	15.00	3.58
	7	110.80—110.35	2400	19000		14.55	14.55	+16.72	+80° L	19	13.60	3.88
	8	110.35—109.95	2164	10200		14.55	16.25	- 0.98	+80° L	19	15.60	4.21
	9	109.95—109.25	3686	8550		16.25	24.16	−16.19	90° L	19	19.34	4.82
	10	109.25—108.75	2608	7400		24.16	25.30	- 7.49	90° L	19	25.40	5.34
	11	108.75—108.36	2072	8300		25.30	22.30	+ 9.42	90° L	19	23.60	5.61
	12	107.10—106.29	4260	6200		28.74	31.48	−14.87	+85° L	20	30.60	6.33
	13	106.29—105.66	3336	5400		31.48	31.62	− 8.23	+85° L	20	32.50	5.85
	14	105.66—104.98	3624	6300		31.62	27.02	+ 7.72	+85° L	20	29.10	5.54
	15	104.98—104.42	2944	7700		27.02	20.95	+15.06	+80° L	14	23.60	5.18
	16	104.42—103.87	2912	11800		20.95	15.35	+18.85	+80° L	14	18.10	3.97
	17	103.87—103.45	2240	20700		15.35	11.24	+29.48	+80° L	14	12.70	3.30
	18	103.45—103.04	2184	24040		11.24	8.70	+31.42	+80° L	14	9.30	2.61
	19	98.05— 97.21	4448	5550		28.20	34.43	−25.77	+75° L	18	31.90	6.76
	20	97.21— 96.29	4856	4950		34.43	35.72	−11.31	+75° L	18	34.80	6.13
	21	96.29— 95.72	2984	3350		35.30	38.50	−29.03	+75° L	18	37.00	7.40
	22	95.72— 94.76	5120	1900		38.50	36.10	− 7.53	+70° L	17	38.80	6.26
	23	94.76— 93.95	4284	2900		36.10	34.30	− 4.93	+70° L	17	34.40	5.45
	24	93.95— 93.24	3736	2500		34.32	33.25	− 7.21	+70° L	17	34.00	5.39
	25	92.48— 91.88	3200	4950		32.70	34.26	−11.88	+75° L	17	33.60	4.93
	26	90.90— 90.29	3232	5050		34.02	34.32	− 8.66	+75° L	17	34.00	5.57
	27	90.29— 89.53	4020	4850		34.32	33.55	− 5.12	+75° L	17	34.30	5.44
	28	89.53— 88.99	2888	5300		33.55	32.29	− 0.73	+75° L	17	32.90	5.09
	29	88.99— 88.29	3684	5450		32.29	31.00	− 1.43	+85° L	13	31.40	4.98
	30	88.29— 87.65	3404	5100		31.00	30.37	− 4.19	+85° L	13	31.00	5.11
	31	87.65— 86.78	4612	5600		30.37	28.62	+ 1.03	+85° L	13	30.00	4.15
	32	86.78— 85.86	4848	7100		28.62	26.60	+ 2.07	+85° L	13	26.50	4.61
	33	85.86— 84.77	5760	8850		26.60	25.23	+ 2.93	90° L	10	27.10	4.49
	34	84.77— 84.36	2136	12500		25.23	25.93	+ 1.98	90° L	10	24.20	4.84
	35	84.36— 83.55	4272	7400		25.93	30.13	−11.98	90° L	10	29.00	4.76
	36	83.55— 83.05	2672	6400		30.13	30.80	− 6.32	90° L	10	30.40	4.80

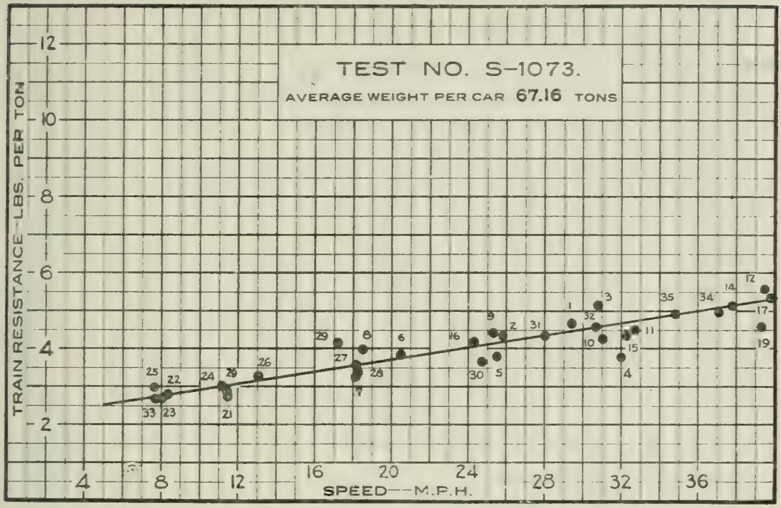
*For complete table heading see Table 36, p. 99.

TABLE 62 TEST NO. S-1073*

From Champaign to Gilman. May 4, 1909. Weather: Fair. Temperature: 53° F. at start, 63° F. at end of test. Total weight behind measuring draw-bar = 1880 tons excluding the test car. Train length = 1200 ft. Center of mass 600 ft. back of measuring draw-bar. 28 cars: 1 empty, 27 loaded. Kind of cars: 27 gondola, 1 caboose. Average weight per car = 67.16 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A_1	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 show Average Values	1	115.97—115.36	3232	10700		29.80	29.10	+ 5.06	+40° R	12	29.40	4.64
	2	114.71—114.21	2618	11000		26.85	25.70	+ 8.18	+50° R	11	25.80	4.31
	3	113.13—112.53	3176	9100		28.65	32.90	—15.60	+45° R	14	30.80	5.13
	4	112.53—111.82	3752	7500		32.90	28.86	+12.52	+45° R	14	32.00	3.78
	5	111.82—111.43	2056	10300		28.86	23.12	+30.60	+45° R	11	25.50	3.79
	6	111.43—111.03	2108	14150		23.12	19.40	+23.30	+55° R	8	20.50	3.82
	7	111.03—110.57	2396	15800		19.39	17.11	+19.80	+55° R	8	18.15	3.27
	8	110.57—109.94	3352	16000		17.11	21.32	+ 3.31	+55° R	8	18.50	3.97
	9	109.94—109.21	3888	11250		21.33	30.13	—16.82	+50° R	12	25.30	4.40
	10	109.21—108.30	4776	8650		30.13	29.68	+ 1.99	+50° R	12	31.00	4.23
	11	107.85—107.44	2160	8350		31.33	34.01	—14.90	+50° R	12	32.70	4.49
	12	106.68—106.08	3188	8200		37.70	40.10	—13.74	+50° R	19	39.50	5.57
	13	106.08—105.45	3292	7250		40.10	39.50	— 1.60	+50° R	19	40.80	5.46
	14	105.45—104.62	4436	7350		39.50	34.62	+11.50	+50° R	19	37.80	5.11
	15	104.62—103.81	4264	8500		35.90	29.20	+18.94	+55° R	14	32.30	4.33
	16	103.81—103.27	2856	10650		29.20	20.60	+ 3.09	+55° R	14	24.30	4.19
	17	96.30— 95.69	3212	2600		37.05	41.25	— 28.90	+40° R	17	39.80	5.32
	19	94.74— 94.31	2304	3000		39.65	37.90	+ 2.75	+35° R	12	39.30	4.57
	20	90.56— 89.99	3012	800		10.34	12.76	— 9.80	+70° R	6	11.42	2.87
	21	89.99— 89.48	2688	750		12.76	9.85	— 1.77	+70° R	6	11.46	2.74
	22	89.48— 88.74	3900	3350		9.85	8.57	— 1.62	+50° R	2	8.32	2.80
	23	88.74— 88.08	3520	4500		8.57	11.15	— 3.45	+ 0°	3	8.01	2.70
	24	87.35— 86.95	2124	1850		10.63	9.70	— 3.73	+25° L	3	11.15	3.00
	25	86.95— 86.32	3308	12200		9.70	10.33	+ 8.54	+ 0°	0	7.65	2.99
	26	86.32— 85.78	2876	11600		10.33	16.04	— 1.74	+ 0°	3	13.07	3.26
	27	85.78— 85.20	3060	8400		16.04	19.96	— 5.87	+15° R	7	18.17	3.53
	28	85.20— 84.75	2416	11200		19.96	16.48	+16.40	+ 5° R	5	18.20	3.32
	29	84.75— 84.30	2372	15500		16.48	21.34	— 3.12	+ 5° R	5	17.20	4.14
	30	84.30— 83.75	2896	10600		21.34	27.31	12.95	+15° R	7	24.70	3.66
	31	83.75— 83.13	3284	9500		27.30	29.70	— 5.62	+45° R	10	28.00	4.33
	32	83.13— 82.66	2480	8800		29.70	32.15	— 12.13	+15° R	12	30.70	4.58
	33	90.94— 90.56	2036	4000		7.05	10.35	6.18	+70° R	6	7.71	2.66
	34	97.22— 96.30	4892	3450		35.90	37.05	11.34	+20° R	12	37.10	1.98
	35	97.80— 97.22	3060	3800		31.75	35.90	21.15	+35° R	11	34.80	4.90

* For complete table heading see Table 36 p. 99.


TEST NO. S-1073.
AVERAGE WEIGHT PER CAR 67.16 TONS
TRAIN RESISTANCE—LBS. PER TON
12
10
8
6
4
2
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36
25
22
33
23
24
29
21
26
29
27
8
28
7
6
16
9
30
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1
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3
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4
15
11
35
34
14
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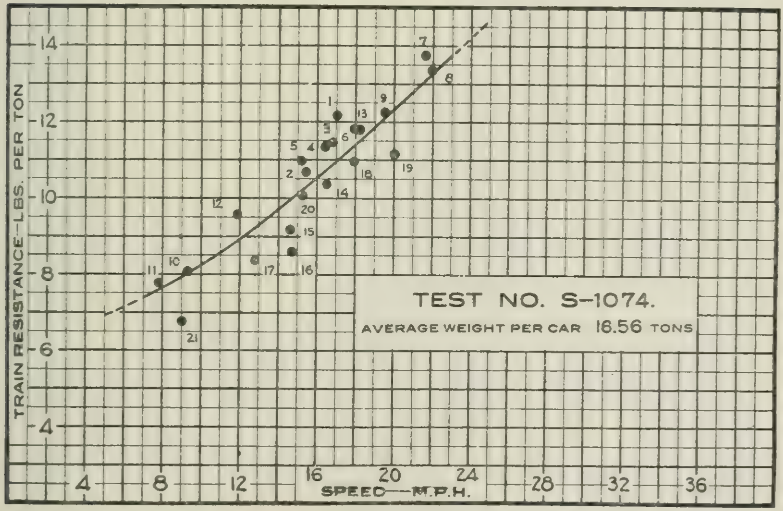
17
19

FIG. 45


TEST NO. S-1074.
AVERAGE WEIGHT PER CAR 16.56 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36
7
8
1
9
13
3
6
5
4
2
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21

FIG. 46

TABLE 63 TEST NO. S-1074*

From Champaign to Mattoon, May 7, 1909. Weather: Fair. Temperature: 45° F. at start, 60° F. at end of test. Total weight behind measuring drawbar = 1340 tons, including the test car. Train length = 3180 ft. Center of mass 1600 ft. back of measuring drawbar. 81 cars: 81 empty, 0 loaded. Kind of cars: 79 gondolas, 1 test, 1 caboose. Average weight per car = 16.56 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel, A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns **5** and 9 to 13 Show Average Values	1	140.88—141.71	4380	13400		17.43	16.35	— 4.10	—80° L	11	17.00	12.16
	2	141.71—142.84	6025	12950		16.35	16.50	— 2.88	—80° L	11	15.40	10.69
	3	142.84—143.77	4930	11000		16.50	17.12	— 9.43	—80° L	11	16.80	11.47
	4	143.77—144.73	3490	11050		17.12	15.46	— 5.41	—85° L	12	16.40	11.34
	5	144.43—145.35	4825	13200		15.46	16.72	— 4.60	—85° L	12	15.20	10.98
	6	145.35—146.21	4600	12600		16.72	20.18	— 11.71	—85° L	12	17.90	11.81
	7	146.21—147.02	4280	10550		20.18	22.35	—19.62	—80° L	10	21.60	13.74
	8	147.02—147.81	4170	11350		22.35	21.54	—10.64	—80° L	10	21.90	13.37
	9	147.81—148.74	4895	12050		21.54	17.82	— 2.81	—80° L	10	19.50	12.25
	10	151.75—152.07	1640	7500		10.90	7.82	+ 0.32	90° L	12	9.30	8.04
	11	152.46—152.86	2076	10000		8.13	8.13	— 0.76	—85° L	9	7.80	7.75
	12	153.50—153.88	2010	10450		12.50	11.40	— 2.10	—85° L	13	11.90	9.56
	13	160.63—161.44	4305	10650		17.43	18.28	11.53	90° L	10	18.20	11.80
	14	161.44—162.20	4016	11300		18.28	14.30	+ 1.18	90° L	10	16.50	10.35
	15	165.08—165.76	3658	14000		13.25	15.55	— 0.14	+65° L	9	14.60	9.18
	16	165.76—166.50	3100	13050		15.55	13.50	+ 5.96	+65° L	9	14.70	8.60
	17	166.50—166.91	2164	15000		13.50	12.68	+ 9.52	+65° L	9	12.84	8.33
	18	169.66—170.41	3936	13500		15.48	20.43	—11.00	+75° L	7	17.90	10.96
	19	170.41—170.82	2200	11250		20.43	19.45	— 3.84	+75° L	7	20.00	11.15
	20	170.82—171.60	4136	15100		19.46	11.07	+15.20	+75° L	7	15.23	10.04
	21	171.60—172.02	2256	23050		11.07	7.91	+32.78	+75° L	7	9.09	6.75

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* For complete table heading see Table 36, p. 99.

TABLE 64 TEST NO. S-1076*

From Champaign to Gilman, May 11, 1909. Weather: Fair. Temperature 51° F. at start, 67° F. at end of test. Total weight behind measuring drawbar-1818 tons, excluding the test car. Train length-1120 ft. Center of mass 500 ft. back of measuring drawbar. 26 cars: 1 empty, 25 loaded. Kind of cars: 25 gondola 1 caboose. Average weight per car-69.92 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 Show Average Values	1	117.91—117.15	3976	8450		28.52	28.80	+ 0.40	+ 55° R	19	28.60	4.23
	2	117.15—116.10	5588	8700		28.80	27.82	+ 3.02	+ 55° R	19	28.20	4.32
	3	116.10—115.38	3820	8900		27.82	27.10	+ 3.87	+ 55° R	19	27.40	4.13
	4	114.77—114.28	2620	11000		24.78	23.70	+ 7.86	+ 60° R	18	23.80	4.44
	5	113.24—112.56	3590	8900		25.95	31.60	—15.60	+ 55° R	21	28.90	4.63
	6	112.56—112.04	2795	7550		31.60	30 02	+ 5.48	+ 55° R	21	31.80	4.45
	7	112.04—111.16	4710	11050		30.02	18.27	+27.70	+ 60° R	17	22.90	3.79
	8	111.16—110.64	2670	14250		18.27	15.09	+18.60	+ 65° R	13	16.50	3.50
	9	110.64—110.34	1575	16000		15.09	15.25	+13.40	+ 65° R	13	11.30	3.51
	10	110.34—109.94	2130	13650		15.25	19.25	— 0.99	+ 65° R	13	17.10	3.19
	11	119.94—109.56	2015	11650		19.25	24.12	—12.83	+ 60° R	17	21.10	4.13
	12	109.56—109.20	1940	9000		24.12	28.75	—21.76	+ 60° R	17	26.40	4.60
	13	109.20—108.30	4700	7950		28.75	27.92	+ 2.70	+ 60° R	17	29.20	4.03
	14	106.93—106.26	3550	7700		35.26	38.38	—14.55	+ 75° R	16	37.10	5 35
	15	106.26 105.34	4855	6250		38.38	37.40	— 2.61	+ 75° R	16	39.00	5.47
	16	105 34—104.25	5780	7050		37.40	30.45	+12.96	+ 75° R	16	34.40	4.53
	17	104.25—103.65	3180	8200		30.98	23.57	+25.08	+ 75° R	16	27.10	3.69
	18	103.65—103.16	2580	12250		23.57	14,80	+30.90	+ 75° R	16	18.50	3 93
	19	98.06— 97.43	3340	2200		30.20	31.75	—26.70	+ 60° R	28	32.50	5.28
	20	97.43— 96.79	3404	1300		34.75	35.75	—11.40	+ 60° R	28	35.60	4.77
	21	90.42— 89.63	4204	650		24.65	23.12	— 6 28	+ 50° R	16	23.90	3.93
	22	87.62— 87.40	1180	7250		4.13	6 93	— 2.24	+ 45° R	5	4.73	3.05
	23	87 40— 86.94	2405	2150		6.93	5.73	— 3.07	+ 45° R	5	8.12	2.77
	24	86.46— 85.84	3288	4950		7.53	8.90	— 1,60	+ 40° R	6	7.88	2.86
	25	85.84— 85.21	3344	2700		8.90	10.33	— 5.53	+ 40° R	6	10.36	3.02
	26	83 88— 83.09	4170	7800		23.00	25.03	— 5.82	+ 60° R	21	23.70	4.90
	27	83.09— 82.40	3652	6100		25.03	27 21	— 9.11	+ 60° R	21	26.20	4.69

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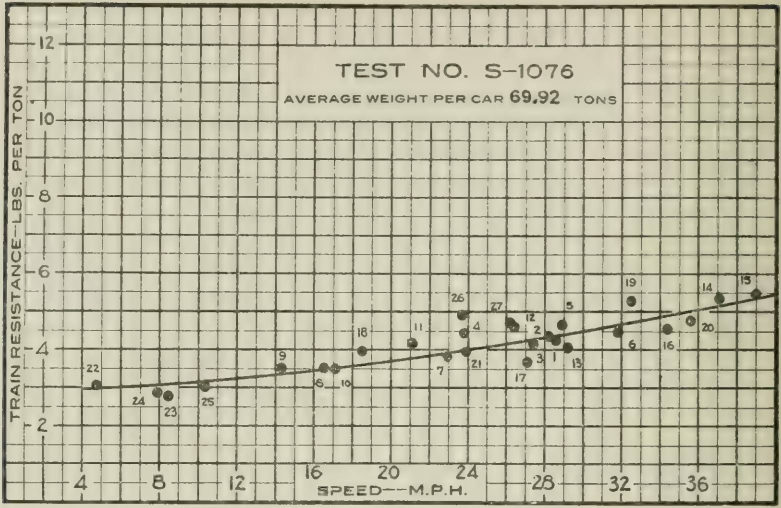
* For complete table heading see Table 36, p. 99.


TEST NO. S-1076
AVERAGE WEIGHT PER CAR 69.92 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
2
4
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8
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FIG. 47

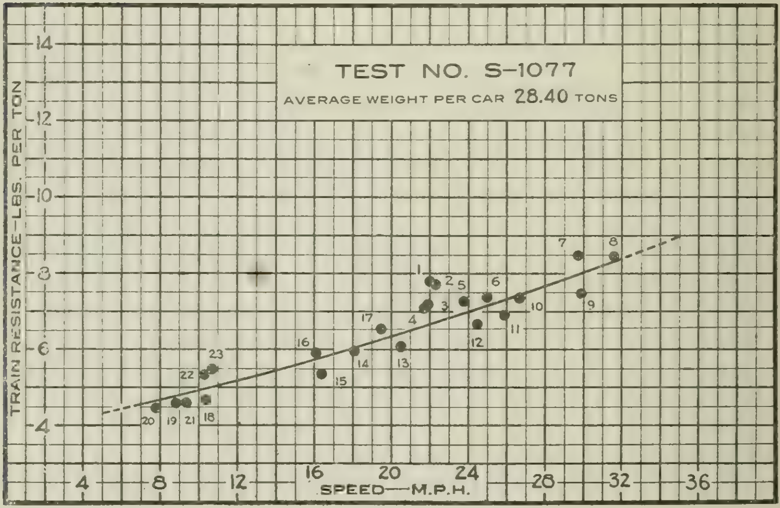
TEST NO. S-1077
AVERAGE WEIGHT PER CAR 28.40 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
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FIG. 48

TABLE 65 TEST NO. S-1077*

From Champaign to Mattoon, May 14, 1909. Weather: Fair. Temperature: 64° F. at start, 70° F. at end of test. Total weight behind measuring drawbar = 1505 tons, including the test car. Train length = 2145 ft. Center of mass 930 ft. back of measuring drawbar. 53 cars: 35 empty, 18 loaded. Kind of cars: 37 box, 14 gondola, 1 test, 1 caboose. Average weight per car = 28.40 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed $V1$	Speed $V2$	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 show Average Values	1	139.56—140.29	3885	8900		22.56	22.18	— 4.10	—65° R	14	22.00	7.77
	2	140.29—141.01	3930	8650		22.18	23.05	— 7.00	—65° R	14	22.30	7.70
	3	141.01—142.03	5785	9000		23.05	21.33	— 0.70	65° R	14	21.90	7.18
	4	142.13—142.85	3820	8850		21.33	23.20	— 7.20	—65° R	13	21.70	7.08
	5	142.85—143.65	4195	8050		23.20	25.15	— 9.20	—65° R	13	23.80	7.26
	6	143.65—144.07	2200	7700		25.15	25.40	— 7.00	—65° R	13	25.00	7.37
	7	146.08—147.07	5235	7000		27.31	31.55	—18.90	75° R	19	29.75	8.47
	8	147.07—148.03	5555	7350		31.55	31.20	— 8.60	—75° R	19	31.60	8.42
	9	148.13—148.62	2630	7350		31.20	29.27	+ 1.40	75° R	19	29.90	7.47
	10	149.09—149.53	2350	8350		27.76	26.72	— 0.20	—75° R	13	26.70	7.33
	11	150.11—150.98	4565	8100		27.09	25.35	— 0.30	75° R	13	25.90	6.90
	12	150.98—151.79	4310	8750		25.35	25.45	— 0.30	75° R	13	24.50	6.65
	13	154.82—155.50	3620	10300		22.45	19.70	+ 7.90	—55° R	12	20.50	6.09
	14	155.50—156.11	3190	11400		19.70	17.25	+ 9.60	—55° R	12	18.10	5.94
	15	156.11—156.65	2900	12450		17.25	16.42	+ 9.50	—55° R	12	16.40	5.35
	16	156.65—157.79	2840	12650		16.42	16.19	+ 7.10	—55° R	12	16.10	5.90
	17	158.01—158.66	3440	11000		18.27	21.52	— 4.90	65° R	12	19.50	6.53
	18	164.89—165.17	1484	6950		10.90	10.18	15.20	30° R	8	10.40	4.66
	19	165.17—165.63	2456	4950		10.18	7.98	— 0.40	30° R	8	8.80	4.59
	20	165.63—166.01	2036	7600		7.98	7.22	— 2.60	—30° R	8	7.80	4.46
	21	166.21—166.53	1664	15000		8.57	10.17	+10.80	—25° R	10	9.40	4.60
	22	166.53—166.87	1812	13500		10.17	10.33	+ 9.30	—25° R	10	10.30	5.31
	23	166.87—167.23	1876	12650		10.33	11.55	+ 5.10	—25° R	10	10.70	5.48

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* For complete table heading see Table 36, p. 99.

TABLE 66 TEST NO. S-1079*

From Champaign to Gilman, May 18, 1909. Weather: Fair. Temperature: 65° F. at start, 68° F. at end of test. Total weight behind measuring drawbar = 1685 tons, excluding the test car. Train length = 2070 ft. Center of mass 1015 ft. back of measuring drawbar. 51 cars: 14 empty, 37 loaded. Kind of cars: 45 box, 5 gondola, 1 caboose Average weight per car = 33.04 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 show Average Values	1	118.04—117.31	3850	10050		22.44	22.04	+ 0.14	+85° R	20	21.80	6.23
	2	117.31—115.99	7035	9700		22.04	19.24	+ 2.56	+85° R	20	20.00	5.93
	3	115.99—115.34	3440	12500		19.24	19.96	+ 3.60	+85° R	20	19.50	5.48
	4	112.92—112.48	2305	10550		25.00	28.27	—14.90	+70° R	21	26.20	6.63
	5	112.48—111.82	3490	8950		28.27	23.62	+ 9.40	+70° R	21	26.50	6.57
	6	111.82—111.37	2380	14200		23.62	16.10	+29.70	+70° R	21	19.10	5.94
	7	111.37—110.79	3070	18550		16.10	13.45	+21.80	+70° R	21	13.50	4.51
	8	110.79—110.16	3310	19750		13.45	15.63	+14.00	+80° R	19	13.25	5.07
	9	110.16—109.83	1760	15000		15.63	18.65	— 1.70	+80° R	19	17.15	5.45
	10	109.83—109.21	3310	9500		18.65	24.92	—16.90	+80° R	19	21.50	6.29
	11	109.21—108.30	4800	6450		24.92	22.30	— 1.00	+80° R	19	24.20	6.01
	12	106.81—106.20	3250	7040		28.98	30.73	—14.30	+80° R	20	29.60	7.36
	13	106.20—105.56	3375	5150		30.73	30.10	— 7.50	+80° R	20	30.70	6.70
	14	105.56—104.96	3180	7750		30.10	25.82	+ 7.80	+80° R	20	27.20	6.89
	15	104.96—104.44	2740	11750		25.82	22.20	+14.60	+80° R	20	23.40	5.85
	16	104.44—103.87	3050	13500		22.20	17.98	+16.80	+65° R	15	19.80	5.52
	17	103.87—103.48	2053	17900		17.98	12.94	+28.00	+65° R	15	14.75	5.31
	18	103.48—103.06	2240	22250		12.94	9.54	+32.10	+65° R	15	10.55	3.40
	19	102.29—101.55	3905	11650		22.10	26.60	— 8.50	+75° R	23	25.40	6.21
	20	101.55—100.48	5685	12650		26.60	22.70	+10.30	+75° R	23	23.50	5.97
	21	100.48— 99.73	3980	12400		22.70	31.34	—19.50	+75° R	23	25.90	6.56
	22	99.73— 98.87	4530	9350		31.34	31.53	— 2.60	+65° R	23	32.60	6.36
	23	98.87— 98.00	4614	11050		31.53	35.70	—12.60	+65° R	23	31.50	7.09
	24	98.00— 97.31	3616	8650		35.60	40.45	—26.30	+65° R	23	37.90	8.00
	25	94.59— 93.65	4970	2700		34.60	32.90	— 7.40	+65° R	16	32.30	6.02
	26	88.97— 88.11	4506	4850		10.10	10.10	— 2.30	—85° R	9	9.17	3.75
	27	88.11— 87.22	4748	3700		10.10	10.10	— 3.30	—85° R	9	9.80	3.45
	28	87.22— 86.76	2428	3100		10.10	5.00	+ 2.60	—85° R	9	8.70	3.06
	29	86.32— 85.81	2645	6450		6.00	8.42	— 1.40	90° R	8	6.95	3.44
	30	84.17— 83.39	4150	10550		20.12	25.95	— 9.70	+75° R	16	23.50	5.42
	31	83.39— 82.46	4920	8600		25.95	28.75	— 9.20	+75° R	16	26.90	6.42

*For complete table heading see Table 36, p. 99.

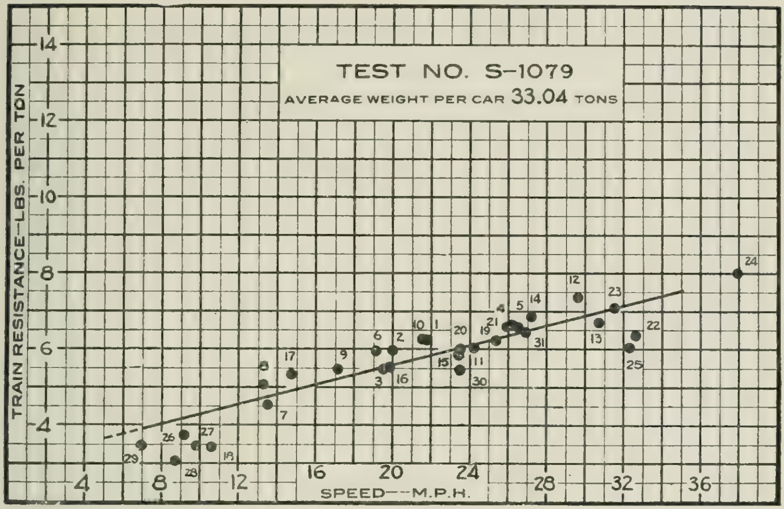
TEST NO. S-1079
AVERAGE WEIGHT PER CAR 33.04 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
4
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FIG. 49

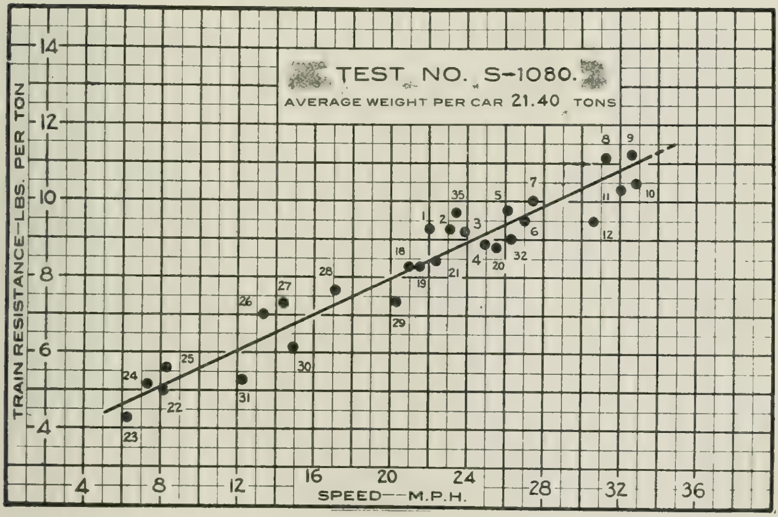
TEST NO. S-1080.
AVERAGE WEIGHT PER CAR 21.40 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
4
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FIG. 50

TABLE 67 TEST NO. S-1080*

From Champaign to Mattoon, May 21, 1909. Weather: Fair. Temperature: 50° F. at start, 70° F. at end of test. Total weight behind measuring drawbar = 1347 tons, including the test car. Train length = 2550 ft. Center of mass 920 ft. back of measuring drawbar. 63 cars: 57 empty, 6 loaded. Kind of cars: 8 box, 53 gondola, 1 test, 1 caboose. Average weight per car = 21.40 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed $V1$	Speed $V2$	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 show Average Values	1	139.61—140.34	3872	11150		22.02	22.70	— 4.09	+30° L	12	22.00	9.27
	2	140.34—140.92	3044	11100		22.70	24.23	— 7.12	+30° L	12	23.07	9.25
	3	140.92—141.71	4192	10700		24.23	23.82	— 2.39	+30° L	12	23.82	9.20
	4	142.67—143.09	2196	10700		24.50	26.10	— 9.38	+25° L	11	24.95	8.86
	5	143.09—143.52	2300	10500		26.10	27.08	— 9.42	+25° L	11	26.14	9.75
	6	143.52—144.42	4752	10050		27.08	26.97	— 5.11	+25° L	11	27.00	9.49
	7	145.29—146.21	4828	10100		26.97	30.13	—13.67	+25° L	11	27.42	10.00
	8	146.21—146.73	2748	9850		30.13	32.35	—19.61	+25° L	11	31.23	11.13
	9	146.73—147.27	2868	9400		32.35	33.25	15.10	+25° L	11	32.60	11.22
	10	147.27—147.81	2888	9450		33.25	33.03	8.23	+ 0°	12	32.81	10.49
	11	147.81—148.35	2820	9650		33.03	31.90	— 3.37	+13° L	10	32.05	10.31
	12	148.35—148.73	2020	10300		31.90	30.62	+ 2.61	+13° L	10	30.60	9.50
	18	159.23—159.58	1844	12250		21.90	20.75	+ 7.16	+45° L	11	20.96	8.29
	19	159.58—160.56	5200	12100		20.75	25.16	5.48	+45° L	11	21.50	8.28
	20	161.33—162.18	4500	9100		27.22	23.56	+ 2.46	+40° L	11	25.56	8.79
	21	162.18—163.25	5244	10800		23.56	23.42	— 0.81	+40° L	11	22.35	8.42
	22	164.97—165.65	3580	6050		8.82	7.22	0.00	+15° L	12	8.14	5.00
	23	165.81—166.23	2212	9000		6.12	5.82	+ 6.68	+15° L	12	6.28	4.27
	24	166.41—166.90	2584	11850		7.52	7.52	+ 9.61	+15° L	12	7.34	5.16
	25	166.90—167.31	2192	10750		7.52	9.20	+ 3.85	+15° L	12	8.30	5.60
	26	168.26—168.71	2348	16850		13.95	13.28	+15.97	+20° L	12	13.34	7.01
	27	168.71—169.29	3060	16050		13.28	16.50	+ 6.21	+20° L	12	14.40	7.30
	28	169.29—169.60	1628	13650		16.50	17.90	+ 0.97	+20° L	12	17.08	7.64
	29	170.83—171.48	3424	12100		23.55	17.20	+18.65	+15° L	11	20.30	7.33
	30	171.48—171.75	1420	17600		17.20	13.70	+32.72	+15° L	11	14.90	6.12
	31	171.75—171.95	1080	20000		13.70	11.80	+33.74	+15° L	11	12.27	5.28
	32	160.56—161.33	4044	9100		25.16	27.22	—10.96	+40° L	11	26.27	9.00
	35	142.28—142.67	2060	12000		23.28	24.50	— 7.44	+25° L	11	23.41	9.71

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* For complete table heading see Table 36, p. 99.

APPENDIX 6

APPENDIX 6

EXACT COORDINATES FOR THE CURVES OF FIG. 10 AND 11.

The original drawings from which Fig. 10 and 11 have been reproduced were drawn to a scale about twice as great as that of the cuts shown in the report. From these original drawings, the values of the coordinates of the various curves of both figures have been determined as accurately as possible; and these values are presented in Tables 68 and 69.

The curves of Fig. 10 (and of Fig. 3 to 9) may be accurately reproduced by the use of Table 68; the curves of Fig. 11 may be reproduced from the values given in Table 69. The tables are presented merely to permit the accurate reproduction, to any scale, of the curves of the report; they are not intended for use in determining values of resistance. For the latter purpose Table 3 is more convenient and sufficiently accurate.

TABLE 68

Values of Resistance for Trains of Various Average Car Weights and for Different Speeds

This table presents the co-ordinates of the original curves from which Figures 3 to 9 and Figure 10 were reproduced.

Average Weight Per Car tons		Train Resistance—Pounds Per Ton							Average Weight Per Car tons	
		Column Headings Indicate the Various Speeds								
		5 m. p. h	10 m. p. h.	15 m. p. h.	20 m. p. h.	25 m. p. h.	30 m. p. h.	35 m. p. h.		
15		7.62	8.20	8.81	9.56	10.37	11.24	12.25		15
	16	7,44	8.00	8.61	9.34	10.13	10.98	11.95	16	
	18	7.10	7.63	8.22	8.92	9.68	10.47	11.39	18	
	20	6.77	7.30	7.85	8.53	9.26	10.00	10.89	20	
	22	6.45	6.97	7.49	8.16	8.81	9.56	10.41	22	
	24	6.16	6.64	7.14	7.79	8.46	9.16	9.94	24	
25		6.02	6.50	6.98	7.62	8.28	8.95	9.72		25
	26	5,88	6.35	6.81	7.44	8.10	8.77	9.52	26	
	28	5.61	6.07	6.51	7.11	7.76	8.40	9.12	28	
	30	5.38	5.80	6.23	6.80	7.43	8.05	8.75	30	
	32	5.13	5.54	5.98	6.51	7.12	7.72	8.40	32	
	34	4.92	5.31	5.72	6.24	6.82	7.40	8.06	34	
35		4.82	5.20	5.61	6.11	6.68	7.26	7.91		35
	36	4.72	5.10	5.50	5.99	6.55	7.11	7.77	36	
	38	4.55	4.90	5.28	5.74	6.29	6.83	7.48	38	
	40	4.38	4.70	5.06	5.50	6.03	6.57	7.20	40	
	42	4.22	4.52	4.88	5.29	5.80	6.32	6.95	42	
	44	4.08	4.38	4.70	5.09	5.59	6.10	6.71	44	
45		4.01	4.30	4.61	4.99	5.49	6.00	6.60		45
	46	3,95	4.21	4.52	4.90	5.38	5.90	6.49	46	
	48	3.82	4.08	4.38	4.71	5.20	5.71	6,28	48	
	50	3.72	3.96	4.24	4.56	5.03	5.52	6.10	50	
	52	3.61	3.85	4.11	4.42	4.88	5.36	5.91	52	
	54	3.52	3.75	3.99	4.30	4.74	5.20	5.74	54	
55		3.48	3.71	3.94	4.25	4.68	5.12	5.67		55
	56	3.43	3.67	3.90	4.20	4.62	5.05	5.60	56	
	58	3.37	3.58	3.81	4.10	4.50	4.93	5.47	58	
	60	3.30	3.50	3.73	4.02	4.42	4.83	5.36	60	
	62	3.23	3.44	3.67	3,97	4.34	4.74	5.27	62	
	64	3.18	3.39	3.60	3.90	4.29	4.68	5.18	64	
65		3.15	3.36	3.58	3.88	4.25	4.64	5.14		65
	66	3.12	3.32	3.55	3.85	4.22	4.61	5.11	66	
	68	3.09	3.30	3.50	3.80	4.18	4.57	5.06	68	
	70	3.05	3.26	3.47	3.76	4.13	4.52	5.01	70	
	72	3.02	3.22	3.44	3.73	4.10	4.49	4.98	72	
	74	3.01	3.19	3.42	3.71	4.08	4.48	4.93	74	
75		3.00	3.18	3.41	3.70	4,07	4.47	4.91		75

TABLE 69

VALUES OF RESISTANCE AT VARIOUS SPEEDS AND FOR TRAINS OF DIFFERENT AVERAGE WEIGHTS PER CAR

This table presents the co-ordinates of the original curves from which Fig. 11 is reproduced

Speed miles per hour	Train Resistance—Pounds Per Ton													Speed miles per hour
	Column Headings Indicate the Average Weights Per Car													
	15 tons	20 tons	25 tons	30 tons	35 tons	40 tons	45 tons	50 tons	55 tons	60 tons	65 tons	70 tons	75 tons	
5	7.62	6.77	6.02	5.38	4.82	4.39	4,01	3.72	3.49	3.30	3,16	3.05	3.00	5
6	7.73	6.86	6.12	5.46	4.90	4.43	4.07	3.77	3.52	3.33	3.19	3,08	3.03	6
7	7.83	6.97	6.21	5.53	4.98	4.50	4.12	3.81	3.56	3.37	3.23	3.12	3.07	7
8	7.96	7.06	6.31	5.62	5.04	4.57	4.18	3.86	3,60	3.40	3.26	3.16	3.10	8
9	8.07	7.18	6.40	5.71	5.11	4.62	4.22	3.90	3.64	3.44	3.30	3.20	3.13	9
10	8.19	7.29	6.50	5.80	5,20	4.69	4.28	3.96	3.69	3.49	3.34	3.24	3.18	10
11	8.30	7.40	6.60	5.90	5.29	4.76	4.33	4.00	3.73	3.52	3.38	3.29	3.21	11
12	8.42	7.51	6.71	5.98	5.37	4.83	4.40	4.04	3.78	3.58	3.42	3.33	3.26	12
13	8.56	7.63	6.81	6.08	5.46	4.90	4.47	4.11	3.83	3.62	3.47	3.38	3.31	13
14	8.70	7.76	6.92	6.18	5.53	4.98	4.53	4.18	3.89	3.68	3.52	3.43	3.36	14
15	8.82	7.88	7.01	6.28	5.64	5.06	4.60	4.24	3.94	3 73	3.57	3.48	3,41	15
16	8.98	8.00	7.12	6.39	5.73	5.13	4.68	4.31	4.00	3.80	3.62	3.53	3.47	16
17	9.10	8.13	7.24	6.49	5.82	5.23	4.75	4.38	4.05	3.86	3.68	3,60	3.52	17
18	9.25	8.27	7.37	6.60	5.92	5.32	4.83	4.45	4.12	3.92	3.74	3.66	3.58	18
19	9.40	8.40	7.49	6,71	6.01	5.41	4.91	4.52	4.19	3.98	3.81	3.72	3.64	19
20	9.56	8.53	7.60	6.82	6.11	5.50	5.00	4.60	4,27	4.04	3.88	3.79	3.71	20
21	9.71	8.69	7.72	6.93	6.22	5.60	5.08	4.69	4.32	4.11	3.94	3.85	3.78	21
22	9.88	8.82	7.86	7.03	6.33	5.70	5.17	4.78	4.41	4.18	4.00	3.92	3.84	22
23	10.02	8.97	7.99	7.14	6.44	5.80	5.27	4.86	4.49	4.25	4.07	3.99	3.92	23
24	10.20	9.11	8.11	7.27	6.55	5.90	5.37	4.94	4.58	4.33	4.15	4.06	3.98	24
25	10.37	9.26	8.25	7.40	6.67	6.01	5.46	5.03	4.66	4.41	4.23	4.13	4.04	25
26	10.52	9.42	8.38	7.52	6.79	6.11	5.57	5.12	4.75	4.50	4.31	4.21	4.12	26
27	10.71	9.57	8.51	7.65	6.91	6.21	5.67	5.22	4.83	4.58	4.40	4.29	4.20	27
28	10.89	9.72	8.67	7.78	7.01	6.33	5.78	5.32	4.92	4.67	4.48	4.38	4.29	28
29	11.06	9.89	8.81	7.91	7.12	6.45	5.88	5.43	5.01	4.76	4,57	4.46	4.36	29
30	11.25	10.03	8.96	8.04	7.26	6.58	5.99	5.53	5.11	4.86	4.66	4.53	4.45	30
31	11.43	10.20	9.10	8.18	7.39	6.71	6 10	5.64	5.21	4.95	4.75	4.63	4.53	31
32	11.63	10.37	9.26	8.31	7.51	6.83	6.21	5.76	5.32	5.04	4.85	4.73	4.62	32
33	11.84	10.53	9.41	8.46	7.63	6.96	6.33	5,87	5.43	5.15	4.95	4.83	4.72	33
34	12.04	10.71	9.57	8.60	7.78	7.08	6.47	5.99	5.54	5.26	5.05	4.92	4.82	34
35	12.25	10.89	9.72	8.75	7.91	7.20	6.60	6.10	5.67	5.36	5.16	5.01	4.92	35
36	12.47	11.07	9.89	8.90	8.04	7.35	6.73	6.23	5.78	5.48	5.27	5.12	5.01	36
37	12.69	11.23	10.04	9.04	8.19	7.49	6.87	6.36	5,90	5.59	5.38	5.22	5.12	37
38	12.91	11.42	10.21	9.20	8.33	7.64	7.00	6.49	6.02	5.71	5.48	5.33	5.22	38
39	13.12	11.61	10.39	9.36	8.48	7.79	7.13	6.63	6.15	5.83	5.60	5.44	5.33	39
40	13.35	11.80	10.55	9.51	8.62	7.93	7.29	6.78	6.28	5.95	5.72	5.55	5.45	40

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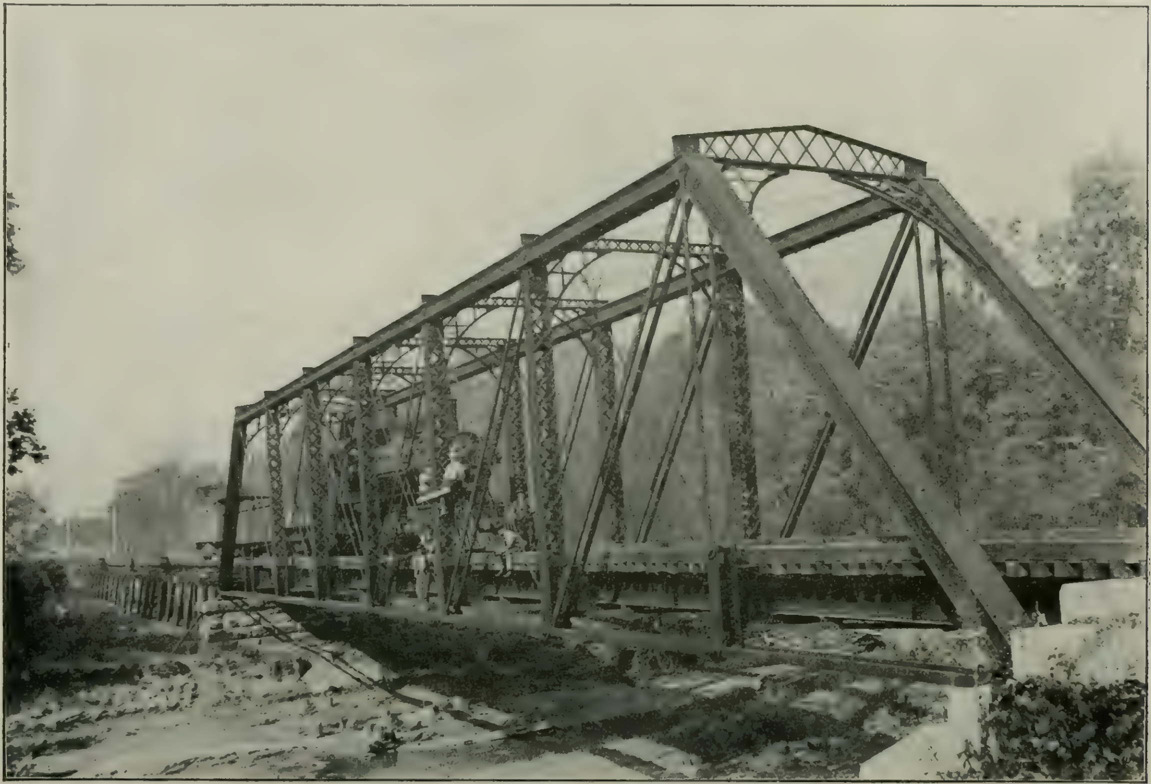

White Heath Bridge and Test Train

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN NO. 44 JUNE, 1910

AN INVESTIGATION OF BUILT-UP COLUMNS UNDER LOAD

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AN INVESTIGATION OF BUILT-UP COLUMNS UNDER LOAD

I. Introduction.

1. *Scope of Bulletin.*—The investigation described in this bulletin was taken up with a view of determining experimentally: (1) something of the way in which the compressive stresses in built-up columns vary over the cross-section of the channels or other component parts and throughout their length; (2) something of the amount and distribution of stress in the lattice bars of columns, and also the action of similar bars under separate tests with similar conditions of fastening and eccentricity; and (3) the general relation which exists between the component parts and the column as a whole. The investigation may be said to differ from the usual tests of columns, where the main purpose is to determine the ultimate strength of the column and the effect of length, in that emphasis is placed on measuring the distribution and range of stress over the various parts of the column. The making of tests to determine the distribution of stress in such compression pieces has commonly been held to be impracticable. In several respects these tests may be said to be pioneer tests along the line of the determination of the distribution of stress under load, whether that load be applied by a testing machine or by a locomotive and train in service.

The principal tests were made on the following compression pieces: (a) a steel column (called Column No. 1) built up of angles, plates, and lattice bars, all the parts being light with respect to the size of the column; (b) four wrought-iron bridge posts which had seen long service in a bridge truss; and (c) three posts and a top chord in a railroad bridge under service. The tests of (a) and (b) were made in a testing machine; for (c) a locomotive and cars formed the load. The auxiliary tests which were made on lattice bars and other parts have an important bearing in connection with the design of columns.

It is well known that built-up compression pieces (whether long or short) are not perfect, the natural imperfections of the component parts being increased in the process of fabrication. To non-homogeneity of structure and lack of straightness in the component angle or channel are added such further imperfections as kinks and eccentric connection of parts, which go to increase the opportunities for local flexure in the component parts and for flexural stresses in the column as a whole. An attempt has been made in these tests to measure the deformations in the presence of such conditions, and to find the general distribution of stress. In view of the many limitations surrounding such tests, the results are to be taken as suggestive and qualitative, and not as exact determinations.

The methods of testing and the results of the tests are given under the heads: II. Laboratory Tests of Columns, III. Field Tests of Columns, and IV. Tests of Lattice Bars, Small Columns, and Column Material. Under V. Discussion, is given a general discussion of the tests and a short discussion of the bearing of the results upon methods of design, together with a summary of the conclusions.

2. *Acknowledgment.*—The steel test column was furnished by the American Bridge Co., Mr. August Ziesing, President. The wrought-iron columns were bridge posts taken from an old bridge of the Chicago, Burlington and Quincy Railroad, and were furnished through the courtesy of Mr. L. J. Hotchkiss, Assistant Bridge Engineer. The arrangement for the test of the railroad bridge was made through Mr. R. E. Gaut, Bridge Engineer of the Illinois Central Railroad, and to him and to Mr. C. R. Westcott, Division Superintendent of the Illinois Central Railroad, special acknowledgment is made for the use of the engine, train, and crew for eight days.

The investigation was the work of the Engineering Experiment Station of the University of Illinois. The observations both in the laboratory tests and the field tests were made by skilled observers, and care was taken to make the tests trustworthy in all respects. Much of the experimental work has been described in Vol. LXV of the Transactions of the American Society of Civil Engineers.

3. *Basis of Column Formulas.*—For the purposes of this discussion a column may be considered to be a prismatic piece, having a length several times its breadth, and subject to nominal axial compression. It is, then, a compression piece in which there is chance for failure at one side of the column by reason of the added stresses of lateral flexure. The column may be a

single solid piece throughout, as in the case of a rolled section, or it may be built up of rolled angles or channels by riveting the members together or by connecting them by plates or lattice bars, as is the usual practice in bridges and other structural steel work.

The analysis ordinarily used in deriving column formulas assumes the existence of flexure in the column as a whole. The deflection in the axis of the column may result from initial eccentricity at the point of application of the load, lack of homogeneity in the material (which will allow bending to begin), a general bend in the column as a whole, or a combination of two or more of these conditions. Except for the initial eccentricity, the amount of the bending moment producing flexural stress is usually assumed to vary as the square of $\frac{l}{r}$ (ratio of length to least radius of gyration). The constants for these semi-rational formulas have usually been obtained by fitting the formulas to the experimental results, and the results of tests have also been used as a basis of purely empirical formulas. Unfortunately, the range of experiments for any given form or type of column has not been large, and especially has information been lacking on the properties of short compression pieces of the character used in the larger columns. In the light of recent tests it seems probable that too much weight has been given to the bending action of the column as a whole and also that, for short and medium lengths, the strength of the column at its elastic limit is not as great, relatively, as it has been considered to be.

Column analysis further assumes the integrity of cross-section of the column; that is, it assumes that the component angles or channels will act as a unit to resist bending so that a plane section before loading will remain plane after loading. It may well be questioned whether the ordinary riveted column does maintain its integrity to such an extent that the whole section will act as a unit. In the case of lightly built columns and of those having parts inadequately laced together, it would seem that the looseness or lack of integrity may greatly affect the distribution of stresses. At any rate, this is a subject which should be investigated before accepting integrity of section as a feature of column action. It will be seen that if the component members or parts of a section act somewhat independently, the conditions of column action will not agree with the usual assumptions. If, for example, the individual parts of a column are very thin, there may be a tendency for these thin parts to wrinkle under compression, and failure by such wrinkling may occur at loads less than would cause the column to fail by direct compression or by bending as a whole. Professor Lilly, of Trinity College, Dublin, has made an experimental study of this wrinkling effect in small columns of various cross-sections.*

Again, it may be noted that in the process of fabrication of the built-up columns, kinks and bends are formed in the component pieces. This condition produces initial stresses and also gives local bending action under load in these pieces. It will be shown that a very slight bend in a thin channel member may cause very severe stresses to be set up. During the process of fitting and riveting in column fabrication the material may be stressed locally beyond the yield point. It would seem reasonable to suppose that a column may have a much different distribution of stress throughout its members than would be expected in an ideal column which would be perfectly straight and homogeneous and which would have its integrity of cross-section preserved under load.

4. *Secondary Stresses in Columns.*—Such conditions as eccentricity of loading, crookedness of column, either general or local, and lack of homogeneity of parts, which act to produce variations in longitudinal stresses throughout the length in the different members of a column, produce transverse shear in the column. To resist this the column parts are riveted together or connected by plates and lattice bars. These shearing forces are usually small, but in the larger columns they become very important. Various attempts have been made to investigate mathematically the distribution and amount of shear in the different parts of a column, but all such analyses depend upon integrity of cross-section and assume a regular change in bending moment from end to middle of column. The conditions attending fabrication of built-up columns seem to make it impracticable to assert with any degree of certainty how far these assumptions may be right. Besides, it is possible that, by reason of conditions

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*The Strength of Columns, Proceedings of the Institution of Mechanical Engineers, June, 1905. The Design of Struts, Engineering (London). January 10, 1908.

resulting from the process of erection, torsional stresses may be set up in the column, and the ordinary column is very poorly adapted to resist such stresses. It seems very desirable that experiments on columns should include a measurement of the stresses in the lattice members.

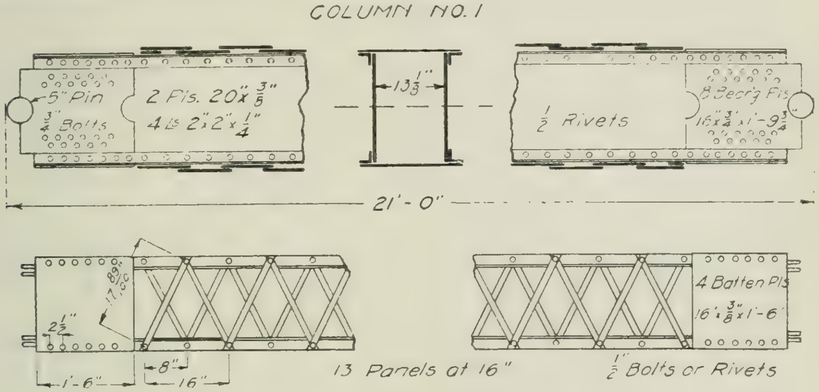

FIG. 1. STEEL TEST COLUMN NO. 1.

5. *Methods of Experimental Study.*—Much of the column testing described in engineering literature has had for its main subject the determination of the ultimate strength of the columns. Observations have been made on the shortening of the column as a whole, and the elastic limit or yield point of the column has been determined. Generally speaking, however, there has been no study of the distribution of deformations throughout the test piece. In outlining the tests described in this bulletin it was believed that a study of the distribution of stress over the cross-section and throughout the length of the column would give results which would be of value. The method adopted was, therefore, to make a measurement of the deformations produced over short spaces at different parts of the column under test and to make these measurements so that the lateral bending of the component pieces of the column could be found. The tests also included the measurement of the deformations in lacing bars and their distribution over the bar. To throw light upon the action of the column, special tests were also made on lacing bars.

II. Laboratory Tests of Columns.

6. *Description of Columns.*—One steel column and four wrought-iron columns were tested. The steel column (designated here as Column No. 1) was specially designed for the purpose of these tests, and was of a much less stocky section than are the built-up columns ordinarily used in bridge and building construction. Fig. 1 shows the details of this column. The section of this column was chosen because it seemed to offer better opportunities than a less flimsy column for the study of distribution of stress, lateral and longitudinal, under the conditions of the test, and also because the stresses developed in the latticing could better be studied. It was thought that the variations of stress due to methods of fabrication, handling in shipment, and conditions of applying the load would be more pronounced than in a

TABLE 1.

Data of Columns.

Column Designation	Column No. 1	Wrought-iron Posts		White Heath Bridge	
		No. 2, 3, 4 and 5	Retest 2a and 4a	Posts U_3L_3 North U_3L_3 South	Upper Chord U_3U_4 South
Area of column section, inches	18.76	17.64	17.64	12.02	48.67
Length, c. to c	21 ft.	15 ft. 10 in.	14 ft. 7 in.	25 ft.	19 ft. 10 in.
End conditions......	Pin parallel to lacing	Pin parallel to lacing	Pin parallel to lacing	Lower end pin, upper end riveted	Riveted
$\frac{l}{r}$ axis parallel to lacing.	37.8	43.5	40.1	66.1	40.7
$\frac{l}{r}$ axis perpendicular to lacing.....	37.2	41.2	38.0	41.0	29.6
$\frac{l}{r}$ of each flange member, axis perpendicular to lacing for full length column......................	593	400	367	416	——
$\frac{l}{r}$ of each flange member, axis as before, for distance between adjacent lacing rivets............	37.7	33.7	33.7	22.2	——
Lattice bars, dimension of section, inches...........	1x¼-in, and 1¼x7/16-in.	2½x⅜-in.	2½x⅜-in.	2¼x⅜-in.	2¾x⅜-in. on bottom
Kind of lacing............	Single	Double	Double	Double; riveted at crossing	One cover plate
Angle of lattice bar with axis of column...........	63° 30′	45°	45°	45°	45° on bottom

stocky column, and hence that the flimsy column would be capable of more accurate study. In this connection it should be noted, however, that the chord members of large bridges are sometimes built up of parts relatively as thin as the parts of this test column. The steel column was built at the Lassig plant of the American Bridge Company. In the earlier tests of this column the lattice bars were fastened in place by turned bolts in reamed holes, and two sizes of lattice bars were used in the different tests, but in the later tests the bars were riveted in place.

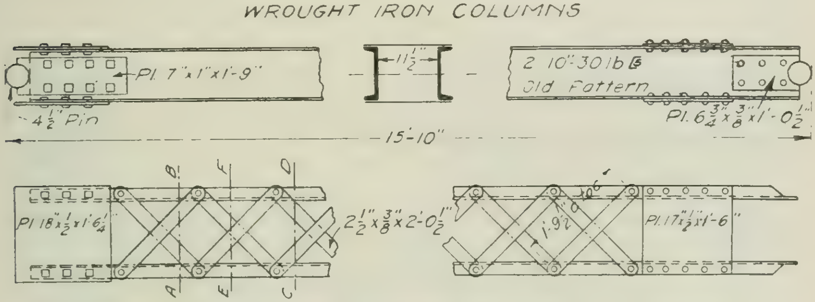
WROUGHT IRON COLUMNS
Pl. 7"x1"x1'-9"
$11\frac{1}{2}$"
2 10"-30 lb
Old Pattern
$4\frac{1}{2}$" Pin
Pl. $6\frac{3}{4}$"x$\frac{3}{8}$"x1'-$0\frac{1}{2}$"
15'-10"
B
F
D
A
E
C
Pl 18"x$\frac{1}{2}$"x1'-$6\frac{1}{4}$"
$2\frac{1}{2}$"x$\frac{3}{8}$"x2'-$0\frac{1}{2}$"
1'-9"
Pl. 17"x$\frac{1}{2}$"x1'-6"

FIG. 2. WROUGHT-IRON TEST COLUMNS NO. 2, 3, 4 AND 5.

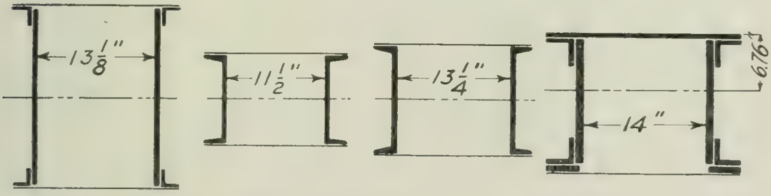

FIG. 3. CROSS-SECTIONS OF TEST COLUMNS.

The wrought-iron columns were from an old bridge of the Chicago, Burlington and Quincy Railroad. For the purpose of the test the posts were cut in two; the old ends were left as used in the bridge, and bearing plates and batten plates were bolted to the other ends. The proportions of these wrought-iron columns represented good practice at the time of the erection of the bridge. The columns became available for testing through the replacement of the bridge by a heavier structure; they were apparently in good condition. Fig. 2 shows the details of one of these columns. Fig. 3 shows to scale the cross-sections of all columns, both in the laboratory and in the field tests. Table 1 gives the general data of all columns tested.

7. *Testing Machine.*—The machine used in testing the columns was the Riehle vertical 600 000-lb. screw-power machine in the Laboratory of Applied Mechanics of the University of Illinois. This machine has a clear space of 36 in. between screws. There is thus room around a column for instrumental work. It will take compression specimens 25 ft. long. It is equipped with a heavy guide frame—not touching any part of the weighing apparatus—which takes any side thrust present in the test. The speed of head in nearly all tests was 0.4 in. per min. The machine has been shown to be accurate and trustworthy.

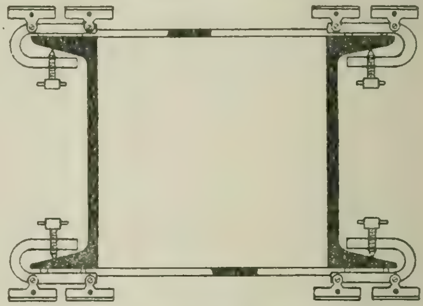

FIG. 4. ATTACHMENT OF EXTENSOMETER TO CHANNEL MEMBERS OF COLUMN.

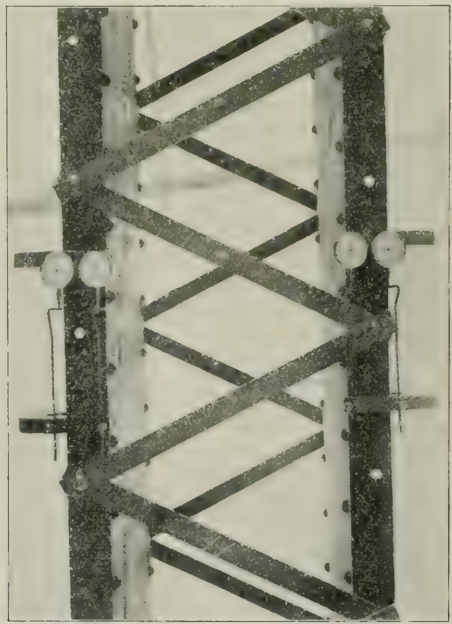

FIG. 5. EXTENSOMETERS IN PLACE ON CHANNEL MEMBERS OF COLUMN.

8. *Extensometers.*—In the earlier testing work various types of extensometers were tried. As a result of the trial the extensometers used in the later tests for measuring deformation in the

channel members consisted of Ames test gauges mounted on suitable frames. Each frame was in the shape of a C-clamp and bore against the channel member through three blunt points and a screw. Fig. 4 shows the shape of these clamps. These instruments magnify change of length by means of clockwork operating a hand rotating over a dial. They read directly to $\frac{1}{1000}$ in. and by estimation to $\frac{1}{10000}$ in. For measuring the deformation of the lattice bars of Column No. 1, a Ewing extensometer was used. In this instrument the displacement of a cross hair is viewed through a microscope. The instrument reads directly to $\frac{1}{5000}$ in., and by estimation to $\frac{1}{50000}$ in. It is a very accurate piece of apparatus but is not adapted to a wide range of size of specimens. It could not be used on the lattice bars of the wrought-iron columns, and on these bars the Ames test gauges were used.

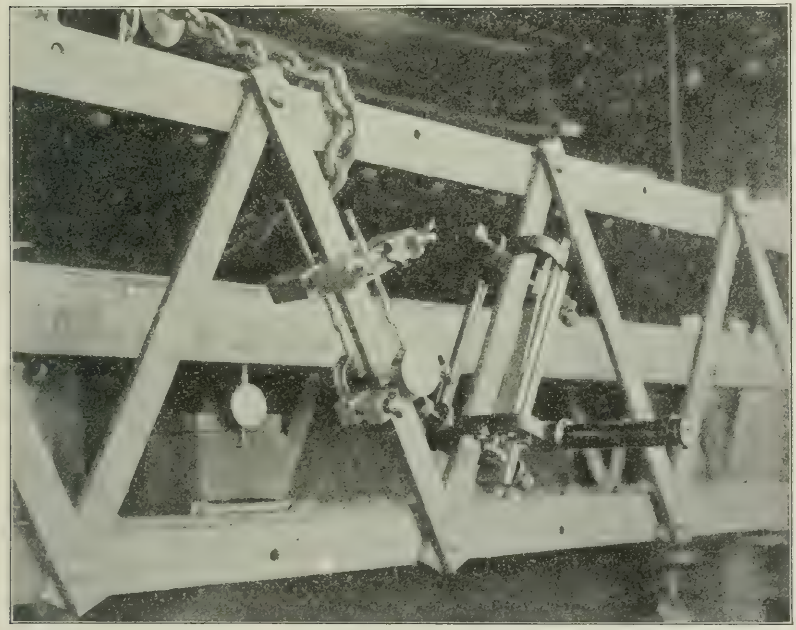

FIG. 6. EXTENSOMETERS IN PLACE ON LATTICE BARS OF COLUMN.

Fig. 5 shows the attachment of the Ames instruments to the channel members of a column, and Fig. 6 shows the attachment of both the Ames and the Ewing instruments to lattice bars.

The magnitude of error liable to be present in the determination of stresses from the readings of the extensometers was studied with some care. The accuracy of all the Ames gauges used was tested by comparison with a Brown and Sharpe micrometer acting through a 10 to 1 lever. The average deviation of a reading of the Ames dial was found to be $\frac{9}{100000}$ in. and the maximum observed deviation $\frac{3}{10000}$ in. The tests covered a range of motion of pointer slightly greater than that observed in the column tests. Basing judgment on the maximum deviation observed in calibration, and on the smallest deformation observed in the columns, it seems probable that the error in stress determination for the channel members is in all cases less than ± 10% and that in general it is much less. This general limit of accuracy is corroborated by a comparison of the average stresses at various cross-sections of the column as determined from the extensometer readings and from the load as indicated by the testing machine. To those accustomed to the apparently greater refinement of many laboratory tests and to the greater precision of calculations frequently employed, the above errors may seem unduly large. However, it may be considered that the instruments gave satisfactory results, especially in view of the large variation of stress

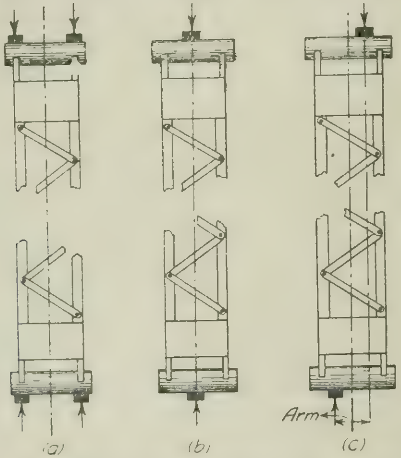

FIG. 7. METHODS OF LOADING: (a) REGULAR CENTRAL LOADING, (b) CENTRAL LOADING, COLUMN NO. 2a AND COLUMN NO. 1 FOR TESTS NO. 11, 12 AND 14, (c) OBLIQUE LOADING, COLUMN NO. 2a, AND COLUMN NO. 1 FOR TESTS NO. 12, 13, AND 15.

distribution over the length of the columns, the general consistency of the results, and the fact that every stress determination is based on more than one reading and also that every conclusion is based on several stress determinations.

As noted above, the Ames test gauges were used to measure deformations in the lattice bars of the wrought-iron columns. On account of the very low stresses in the lattice bars it is felt that the stresses determined in them may be in error by ± 20%. In measuring the deformation of the lattice bars of Column No. 1 with a Ewing extensometer, the accuracy was greater, and the errors in determination of stress in lattice bars of Column No. 1 are probably not greater than ± 10%.

The Ames test gauges were light, durable, easily read, and adapted to a very wide range of conditions. In other tests they had successfuly withstood hard service. Any available instrument of greater precision would have been too bulky or too liable to injury or derangement of parts under the severe conditions of test, and especially under the conditions of field tests of columns.

9. *Procedure of Tests.*—The stress distribution was studied by measuring the compression or shortening over a short distance longitudinally. This measurement was made at several places in the cross-section. The dials were placed slightly outside the column, and the deformation along the extreme fibers of the channel members was later computed on the assumption for each channel member that a section plane before deformation remains plane after deformation. This hypothesis is not dependent upon the integrity of the column as a whole, but only upon that of the individual channel members. The position of the instruments at one location is shown in Fig. 5 (p. 12). As the elastic limit was not exceeded in the tests of stress distribution, in the interpretation of the data the stress in the piece is assumed to be proportional to the deformation. Necessary shifting of instruments and repetition of load made the test proceed very slowly. In studying the stress distribution of Column No. 1 for each method of loading it was necessary to apply the load about three hundred times. This took about three days of actual work after the column was adjusted in place. For each position of the instruments the load was applied and readings taken at least twice, frequently three times, and in cases where especially large readings, or especially small readings, were noted, five to ten readings were taken.

A similar procedure was followed in the tests of lattice bars in the study of stress distribution in them.

TABLE 2.

STRESSES IN COLUMN NO. 1.

Stresses are given in pounds per square inch.

Panel	NORTH CHANNEL						SOUTH CHANNEL					
	West Side			East Side			West Side			East Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
TEST NO. 1.												
1	8 100	10 200	10 600	12 200	10 000	9 700	6 500	8 400	8 600	9 600	10 900	11 300
2	9 700	10 100	10 100	8 100	9 600	10 000	11 900	11 500	11 600	8 900	10 500	11 100
3	7 500	10 200	11 000	11 800	10 000	9 700	11 500	9 800	9 800	9 000	10 300	11 000
4	10 500	10 000	10 000	10 500	11 000	11 000	9 000	8 600	8 600	10 800	10 100	10 500
5	9 600	9 100	9 100	10 900	9 700	9 500	10 300	8 500	9 700	8 800	10 100	10 600
6	9 900	11 000	11 100	10 000	9 600	9 700	9 400	8 400	8 100	9 000	9 200	9 100
7	10 000	7 600	6 900	11 000	10 000	9 900	9 000	9 400	9 900	9 200	10 000	10 400
8	8 100	8 900	9 000	10 800	11 300	11 500	12 700	10 500	10 400	12 200	10 100	10 300
9	10 000	11 000	11 100	9 400	11 000	11 000	14 500	10 000	9 000	9 000	9 200	9 200
10	14 000	10 000	9 300	14 300	11 800	11 000	5 400	8 900	9 300	7 200	9 600	10 000
11	8 600	9 500	9 600	10 000	9 800	9 600	9 000	8 800	8 400	9 800	11 000	11 400
12	12 300	9 200	8 700	9 100	9 400	9 800	10 800	9 300	9 000	10 700	9 600	9 500
13	……..	……..	……..	8 700	8 800	9 000	7 800	9 000	9 200	……	……	…….
TEST NO. 2.												
6	11 500	12 100	12 100	11 500	10 000	9 500	9 100	9 000	9 300	5 800	7 500	7 700
7	12 200	12 600	12 700	14 600	13 500	13 300	5 900	7 500	8 000	8 300	9 500	9 500
8	11 300	12 500	12 800	12 400	12 500	10 600	7 800	8 200	8 300	7 500	10 300	10 700
9	14 800	13 300	12 700	9 500	10 500	10 600	11 800	7 300	7 000	10 300	8 400	8 300
10	9 000	10 200	10 400	16 200	10 500	9 600	7 800	10 500	11 400	9 000	8 400	8 500
11	15 200	10 200	9 700	13 700	11 600	11 500	7 600	8 100	8 300	5 000	6 300	8 600
12	10 300	11 900	12 300	12 700	11 600	11 500	9 400	8 200	7 700	7 000	7 500	9 700
13	13 200	11 800	11 700	9 900	10 500	10 800	7 500	8 600	9 100	6 300	6 300	8 400
TEST NO. 3.												
1	……..	……..	……..	13 800	10 400	9 500	7 500	8 800	8 900	……	……	…….
2	8 900	10 600	10 900	8 800	10 400	10 600	8 300	9 300	9 400	10 000	9 700	9 700
3	10 500	9 800	9 800	8 700	9 000	9 200	10 400	8 700	8 700	11 900	10 500	10 300
4	9 800	10 800	11 000	11 100	10 700	10 700	8 300	8 300	8 500	13 300	12 600	12 200
5	10 500	10 000	9 800	11 200	10 700	10 700	9 000	10 000	10 100	9 300	9 500	9 400
6	11 300	12 300	12 500	10 900	10 500	10 700	10 400	9 700	9 500	7 500	9 400	9 600
7	10 400	10 700	10 700	11 900	11 000	10 800	9 200	10 000	10 000	8 400	8 800	8 800
8	12 100	10 200	10 200	12 100	13 000	13 100	8 500	9 300	9 400	7 300	9 000	9 400
9	7 600	9 900	10 200	10 500	10 900	10 800	14 400	9 300	8 400	10 900	10 600	10 700
10	10 500	12 000	12 100	14 200	11 000	10 500	7 200	10 400	10 900	7 800	8 700	8 700
11	14 200	10 500	9 700	7 500	8 500	8 600	8 300	9 400	9 300	7 000	9 400	9 800
12	10 400	12 000	12 200	6 500	7 500	7 800	11 000	9 300	9 000	7 900	9 100	9 400
13	12 600	9 800	9 500	8 300	8 400	8 200	7 200	9 800	10 200	11 000	10 800	10 900

TABLE 2—(*Continued*).

STRESSES IN COLUMN NO. 1.

TEST NO. 4.

Panel	North Channel						South Channel					
	West Side			East Side			West Side			East Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
1	......	......	......	......	......	......	......	......	......	......	......	......
2	11 300	10 8000	10 700	10 500	11 100	11 200	6 100	3 000	2 500	8 900	10 200	10 600
3	10 000	11 6000	11 600	10 100	11 100	11 100	8 400	8 500	8 500	12 000	11 300	11 100
4	11 200	12 3000	12 500	9 900	10 900	11 000	7 600	9 400	9 700	7 900	9 300	9 500
5	......	......	......	12 800	11 100	10 700	......	......	......	10 700	10 200	10 100
6	10 100	5 400	4 500	12 800	10 700	10 300	6 500	8 900	9 500	......	......	......
7	8 000	10 600	11 000	10 200	9 700	9 700	......	......	......	8 700	8 500	8 600
8	9 800	12 000	12 400	9 700	10 000	10 100	9 000	9 400	9 400	10 300	11 300	11 400
9	11 500	10 600	10 400	......	......	......	8 500	10 700	10 900	7 900	11 100	11 500
10	8 600	8 300	8 100	6 800	8 700	9 100	10 800	7 500	7 000	9 300	10 700	11 000
11	......	......	......	......	......	......	9 500	9 000	8 900	13 000	12 700	12 600
12	10 900	10 400	10 300	10 700	9 900	9 600	......	......	......	......	......	......
13	11 000	10 700	10 700	11 100	10 600	10 500	7 300	9 800	9 600	12 700	11 900	11 800

TEST NO. 5.

Panel	North Channel						South Channel					
	West Side			East Side			West Side			East Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
½	12 100	10 400	9 300	11 000	9 500	8 700	9 700	10 500	10 900	10 400	10 800	10 900
1	9 800	11 100	11 800	10 000	10 200	10 500	12 200	10 400	9 300	13 500	11 300	10 400
1½	7 900	8 500	8 600	5 800	8 200	8 900	7 300	8 400	8 900	7 400	7 900	8 300
2	11 800	11 400	11 100	10 900	10 600	10 600	8 500	8 600	8 700	9 800	10 200	10 400
2½	10 700	11 000	11 100	10 800	10 200	10 200	11 800	11 900	11 800	9 700	9 700	9 600
3	5 800	7 500	8 500	7 800	8 000	8 500	8 300	8 500	8 600	7 700	9 100	9 700
3½	8 000	8 100	8 500	7 400	8 100	8 500	7 800	8 600	9 000	7 500	7 600	7 700
4	15 400	13 000	12 400	13 500	13 000	12 800	11 600	11 800	11 800	9 900	9 900	9 900
4½	12 200	10 700	10 300	12 200	10 200	9 200	9 900	9 900	9 800	9 800	9 800	9 700
5	9 400	9 500	9 600	11 000	10 100	9 600	9 700	9 500	9 500	8 900	9 800	9 900
5½	9 900	10 700	11 100	10 500	10 900	11 000	10 900	9 100	8 300	8 700	8 800	8 900
6	7 400	7 300	7 200	8 100	9 200	9 700	13 800	11 900	11 100	11 100	10 600	10 200
6½	10 900	10 200	9 700	10 200	10 300	10 500	8 600	8 900	8 900	8 500	8 600	8 600
7	12 100	11 700	11 400	11 400	10 900	10 400	8 300	8 800	8 900	5 900	7 900	8 700
7½	9 900	9 200	8 900	9 600	9 400	9 500	6 500	7 600	8 300	4 600	6 400	6 900
8	9 800	8 600	8 300	8 100	9 700	10 400	11 400	9 500	8 500	12 700	10 800	10 100
8½	9 200	9 700	10 000	9 700	9 500	9 300	20 200	15 400	13 100	15 400	14 000	13 200
9	6 500	7 600	8 300	9 700	9 700	9 900	12 900	13 200	13 100	9 400	9 900	10 200
9½	10 000	10 400	10 600	12 900	9 500	8 100	4 600	7 800	8 900	4 600	7 300	8 500
10	16 400	12 900	11 200	17 000	14 400	12 900	8 000	8 600	8 700	6 800	8 000	8 600
10½	11 300	10 700	10 400	9 900	10 000	9 700	10 500	11 100	11 300	7 400	8 900	9 600
11	7 000	8 400	8 900	8 100	9 100	9 600	12 600	11 100	10 800	9 800	10 800	11 000
11½	9 700	8 900	8 600	11 900	10 500	9 700	8 200	11 100	11 700	8 900	9 700	9 800
12	14 000	12 400	11 600	11 900	11 000	10 400	6 900	7 500	7 800	8 100	8 800	9 400
12½	9 700	8 900	8 600	10 500	12 100	12 700	10 800	11 800	12 400	11 900	11 000	10 800

TABLE 3.

STRESSES IN WROUGHT-IRON BRIDGE POSTS.

Panel	NORTH CHANNEL						SOUTH CHANNEL					
	West Side			East Side			West Side			East Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
	COLUMN NO. 2, TEST NO. 6.											
1	4 600	6 500	7 300	6 400	7 900	8 500	4 300	8 300	9 700	5 000	6 800	7 400
2	7 300	7 300	7 300	8 300	8 400	8 400	9 800	9 000	8 800	9 000	8 000	7 600
3	5 500	5 900	6 000	7 100	7 800	8 000	7 700	8 800	9 200	6 700	7 600	7 900
4	6 200	6 100	6 200	6 100	6 900	7 100	8 400	8 800	9 000	8 200	8 000	8 000
5	7 200	6 500	6 100	8 800	8 600	8 500	7 500	8 800	9 300	8 700	7 800	7 500
6	6 800	6 900	6 900	8 400	8 400	8 400	7 100	7 600	7 800	6 900	7 200	7 400
7	7 500	7 900	8 000	7 100	7 400	7 500	7 500	8 200	8 500	7 500	7 400	7 300
8	6 400	7 400	7 800	6 200	7 200	7 600	7 700	7 900	8 000	6 600	6 400	6 100
	COLUMN NO. 3, TEST NO. 7.											
1	9 300	9 000	9 000	8 400	9 500	10 000	10 000	9 000	10 100	8 200	8 000	7 900
2	10 200	10 000	9 900	10 200	11 500	11 900	8 400	9 100	10 000	9 100	8 700	8 500
3	8 800	8 700	8 600	9 800	10 000	10 000	10 000	9 700	9 600	9 400	9 600	9 600
4	10 500	9 100	8 600	8 500	9 500	9 900	8 600	9 800	10 200	9 300	7 500	6 900
5	10 200	10 400	10 500	8 800	9 600	9 900	10 100	9 800	9 700	10 400	10 200	10 200
6	10 600	10 000	9 800	10 300	10 000	10 000	10 400	10 400	10 400	10 000	9 900	9 900
7	10 300	9 900	9 700	9 600	9 900	10 000	8 700	9 500	9 700	10 900	10 000	9 700
8	9 800	9 600	9 500	10 200	10 900	11 000	7 600	9 600	10 300	7 800	9 900	10 600
	COLUMN NO. 4, TEST NO. 8.											
1	9 000	9 800	10 000	10 000	10 700	11 000	8 200	10 000	10 800	9 000	9 200	9 300
2	8 700	9 300	9 500	10 100	10 800	11 100	10 100	11 600	12 100	8 600	9 400	9 700
3	9 300	9 800	9 900	10 800	11 200	11 400	10 000	10 200	10 200	7 400	8 400	8 700
4	9 500	9 700	9 800	11 100	10 200	10 000	9 700	11 100	11 600	7 100	8 200	8 500
5	10 200	10 500	10 600	11 900	12 400	12 600	8 400	9 400	9 800	7 700	8 800	9 200
6	11 600	12 000	12 100	12 400	13 600	13 900	9 500	10 800	11 100	7 400	9 500	10 200
7	12 800	12 500	12 400	13 400	14 200	14 600	7 100	8 300	8 700	6 400	6 700	6 700
8	8 600	11 600	12 700	13 000	11 300	10 700	6 600	8 500	9 200	6 200	7 800	8 400
	COLUMN NO. 5, TEST NO. 9.											
½	14 000	11 700	10 800	12 600	11 700	11 400	7 400	8 100	8 400	7 400	7 900	8 000
1	11 300	12 000	12 300	11 100	10 000	9 600	6 700	8 500	9 200	5 100	6 800	7 500
1½	11 300	11 100	11 100	11 100	10 800	10 700	5 700	6 200	6 300	6 600	6 900	7 100
2	13 100	12 600	12 400	12 900	12 400	12 200	8 000	8 000	8 000	7 800	8 200	8 300
2½	12 700	12 000	11 700	13 100	11 500	11 100	9 300	9 200	9 200	8 700	8 400	8 300
3	11 800	12 000	12 200	11 400	12 200	12 400	8 200	8 400	8 400	6 300	8 000	8 600
3½	13 500	10 500	9 300	11 600	10 700	10 400	8 200	8 200	8 200	8 400	8 300	8 200
4	14 300	13 100	12 700	14 300	12 300	11 500	7 300	7 400	7 500	7 400	8 700	9 200
4½	11 600	11 600	11 500	12 300	12 300	12 300	9 000	9 000	9 000	8 700	8 700	7 800
5	12 600	12 400	12 300	11 700	10 400	10 000	8 300	8 400	8 400	7 400	8 500	8 100
5½	13 700	12 100	11 500	13 500	12 100	11 400	8 300	8 300	8 300	8 400	8 400	7 600
6	12 600	12 700	12 700	13 500	12 500	12 200	7 600	7 600	7 600	7 200	7 000	7 100
6½	13 100	11 900	11 500	11 400	11 400	11 500	8 400	8 400	8 400	10 500	9 000	8 500
7	11 100	11 300	11 500	11 200	12 300	12 600	7 900	8 000	8 000	6 500	8 100	8 600
7½	10 600	10 100	9 900	11 000	10 300	9 900	8 000	8 200	8 200	5 900	7 900	8 700
8	10 300	12 300	12 800	11 300	12 300	12 400	8 500	8 600	8 600	10 800	11 800	12 200

TABLE 3—(*Continued*).

Panel	NORTH CHANNEL						SOUTH CHANNEL					
	West Side			East Side			West Side			East Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
COLUMN NO. 4a, TEST NO. 10.												
½	8 100	9 500	10 200	8 400	8 100	8 000	11 700	10 800	10 500	9 900	11 200	11 800
1	8 300	10 200	10 800	6 500	7 200	7 500	12 100	10 900	10 400	11 100	12 500	13 100
1½	8 400	9 400	9 700	7 400	8 200	8 400	12 100	11 400	11 100	11 000	11 400	11 600
2	8 700	8 800	9 000	6 200	7 200	7 500	10 800	10 500	9 700	9 300	11 700	12 600
2½	8 300	8 800	9 000	7 300	6 900	6 800	11 800	11 500	12 100	10 900	10 400	10 300
3	8 700	9 700	9 900	6 700	6 500	6 400	13 300	11 100	10 400	10 400	11 100	11 400
3½	8 300	8 000	8 000	7 300	7 300	7 400	13 600	11 600	11 100	13 000	12 400	12 400
4	8 200	9 700	10 100	6 800	6 900	6 800	14 300	13 500	12 700	13 100	11 100	10 500
4½	7 500	8 600	9 100	6 300	7 200	7 500	12 300	11 100	10 800	10 300	15 200	9 400
5	7 500	8 400	8 800	7 000	8 100	8 500	13 000	13 300	13 500	9 000	11 400	12 300
5½	6 300	7 200	7 500	5 900	6 100	6 200	12 700	12 300	12 100	12 300	10 700	10 100
6	6 800	7 800	8 200	5 300	6 800	7 200	14 200	14 200	14 200	11 000	11 200	11 300
6½	6 600	7 800	8 200	7 100	7 100	7 100	15 400	13 700	12 900	13 500	11 500	11 100
7	6 700	7 100	7 200	4 900	6 100	6 700	11 900	13 600	14 600	11 100	12 100	12 400
7½	6 100	7 600	8 300	4 800	8 100	9 400	12 300	12 400	12 400	9 300	16 200	11 100
8	6 000	8 200	9 000	8 400	6 800	6 200	10 700	12 200	12 800	10 000	16 300	11 100
COLUMN NO. 2a, TEST NO. 11.												
½	11 600	10 900	10 400	11 400	10 500	10 000	....	....	....	....	....	....
1	7 300	9 300	10 000	7 300	9 700	10 400	8 400	8 800	9 000	10 200	10 200	10 200
1½	11 600	9 900	9 600	11 600	10 900	10 000	8 500	10 000	10 600	11 400	12 000	12 200
2	8 900	8 700	8 600	10 500	10 300	10 000	10 200	9 000	8 600	11 500	11 200	11 000
2½	11 200	9 700	9 200	10 900	10 300	10 000	9 900	10 000	10 200	11 700	10 300	9 900
3	9 500	10 500	10 700	12 200	10 800	10 000	11 800	10 200	10 800	11 400	10 600	10 300
3½	10 500	11 000	11 000	12 100	10 600	10 000	10 400	8 600	8 100	9 700	9 600	9 400
4	9 800	9 500	9 400	10 600	9 900	9 600	9 800	9 400	9 200	10 400	10 600	10 500
4½	10 300	9 600	9 300	11 200	10 200	10 000	8 700	9 600	10 400	10 400	10 000	10 000
5	9 600	9 800	9 900	10 400	10 800	11 000	10 300	9 200	8 800	10 400	10 200	10 200
5½	12 200	11 600	11 200	12 000	11 100	10 700	12 500	10 400	10 000	12 200	11 900	11 700
6	10 100	9 700	9 700	9 900	9 700	9 700	9 100	10 400	10 900	10 300	10 700	10 700
6½	11 300	11 000	10 800	10 600	9 900	9 700	10 800	9 900	9 700	11 000	11 000	10 000
7	9 300	9 600	9 700	9 100	9 300	9 200	9 800	9 800	9 800	9 800	10 800	10 000
7½	10 200	10 900	11 400	9 100	9 400	9 500	9 300	9 600	9 800	9 900	10 700	10 800
8	9 900	9 800	9 700	11 100	10 000	9 600	8 800	10 300	10 900	10 800	10 700	10 800
COLUMN NO. 2a, TEST NO. 12.												
½	10 600	10 000	9 800	10 400	10 600	10 600	11 500	10 600	10 000	13 200	12 600	12 300
1	8 400	8 400	8 500	9 700	10 800	11 200	9 800	10 700	10 900	10 000	11 300	11 700
1½	8 200	8 000	7 900	9 200	10 600	10 900	9 200	9 600	9 700	8 800	10 000	10 200
2	9 200	9 800	10 000	9 900	10 900	11 300	11 400	10 000	9 400	12 200	11 400	11 000
2½	10 800	9 900	9 600	10 800	9 600	9 100	10 900	10 900	10 900	11 400	11 600	11 600
3	9 100	10 800	11 200	11 000	10 600	10 400	10 600	11 200	11 300	10 400	10 200	10 100
3½	10 700	10 900	10 800	12 000	10 600	10 000	10 600	10 900	10 900	10 200	10 600	10 600
4	10 000	8 800	8 400	11 400	9 400	9 400	8 900	10 000	10 300	8 800	10 300	10 900
4½	10 600	10 000	9 900	10 200	10 000	9 900	10 000	10 100	10 200	8 600	9 500	9 800
5	10 100	10 300	10 400	11 300	11 000	11 000	11 800	10 200	9 600	10 200	9 700	9 700
5½	10 900	11 300	11 300	11 400	10 600	10 300	13 000	11 000	10 400	11 000	9 500	9 000
6	11 500	10 800	10 500	9 500	9 000	9 000	9 500	9 900	10 000	9 700	9 500	9 500
6½	11 700	9 800	9 200	12 700	10 300	9 600	10 000	10 000	10 000	9 600	10 300	10 600
7	9 900	11 300	11 600	9 900	11 100	10 600	10 500	9 800	9 300	9 600	10 000	10 000
7½	8 000	9 700	10 300	15 400	15 400	15 400	7 800	10 000	10 600	6 800	8 500	9 000
8	10 000	9 800	9 900	11 700	10 100	9 900	8 800	10 400	11 100	9 400	9 400	9 400

TABLE 3—(*Continued*).

COLUMN NO. 2a, TEST NO. 13.

Panel	NORTH CHANNEL						SOUTH CHANNEL					
	West Side			East Side			West Side			East Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
1	4 500	7 000	8 600	7 000	8 600	9 100	9 800	10 800	11 100	10 300	12 300	13 000
2	7 600	9 000	9 500	10 300	10 400	10 600	10 900	10 100	9 700	12 800	12 600	12 600
3	7 000	8 600	9 100	9 400	10 100	10 300	11 300	11 300	11 300	11 600	12 600	13 000
4	8 100	9 100	9 500	10 400	10 800	10 900	9 300	10 400	10 700	9 600	11 600	12 500
5	8 200	9 500	10 000	10 000	10 200	10 200	10 900	8 900	8 100	10 600	10 700	10 800
6	10 000	10 400	10 600	10 500	10 000	10 000	8 500	9 600	10 000	9 600	10 400	10 800
7	9 800	9 800	9 900	10 200	10 300	10 300	9 500	8 800	8 700	9 900	10 000	10 100
8	8 000	7 800	7 700	12 300	10 300	9 200	7 700	8 700	9 100	8 700	10 000	10 500

10. *Method of Loading.*—Two methods of loading were used, central and oblique. In all cases the load was applied to the end of the column through the pins, and in a plane passing through the nominal axis of the column and paralled to the lacing. In central loading the pin was adjusted to an even bearing on the machine. In oblique loading the pin was supported on a narrow block as shown in Fig. 7 in such a way as to secure a given eccentricity. The center of the block was taken as the point of application of the load. This assumption is approximately correct, the error being probably not greater than $\frac{1}{4}$ in. In two tests of Column No. 1, the point of application of load is somewhat uncertain, as by an oversight the two bearing blocks were not placed symmetrically with respect to the axis of the column. Probably the loading was nearly central.

11. *Routine of Tests for Stress Distribution.*—In a test for stress distribution, the column was placed in the machine and a light initial load was applied. The extensometers were then attached in position to measure the deformation at some point of the column, and an initial reading was taken. A known load was applied by the testing machine and the instruments were read again. The load was then released to its initial value and another application of the load was made. If the second readings did not exactly check the first, further applications of the load were

made. In cases where the observed deformations were large or seemingly abnormal, the test was repeated at another time, and in some cases as many as ten observations were made on the same gauged length. In some of these cases the instruments were reset, their places being exchanged. The instruments were next attached in a new location, and the process was repeated. Thus the stress distribution in various parts of the column was finally determined.

The above method of changing instruments from position to position is practically necessary, as the expense of providing a sufficient number of extensometers to measure the deformation in every panel of the column would be very great.

The load generally used in the laboratory tests was 10 000 lb. per sq. in. of section of the column in excess of the initial load.

12. *Results of Tests for Stress Distribution.*—Tables 2 and 3 give results of the tests to determine stress distribution and variation in the flange members found in thirteen of the column tests. The stresses given are calculated from the observed deformation, using for the modulus of elasticity 28 000 000 lb. per sq. in. for steel and 26 000 000 lb. per sq. in. for wrought-iron, these values checking closely with the total shortening of the columns and with the average deformations observed throughout their length. As heretofore described, the stress noted is the average over a space of 4 in. or 4½ in. on either side of the point indicated. Any lack of agreement between the average stress on the center of gravity of the flange members and the average stress for the load applied is probably due principally to instrumental errors.

Fig. 8 to 15 show graphically the stress distribution and variation. The full line gives the stress at the east side (back) and the dotted line at the west side (front).

Table 4 gives a number of the most marked deviations from average stress. The excess of the maximum fiber stress is given as a percentage of the average stress.

In most cases the maximum stress was in the outer fiber of the channel; sometimes very high stresses were found in the inner fiber. Generally, the stress in the opposite channel was correspondingly less.

13. *Stress in Lattice Bars.*—Table 5 gives the results of tests to determine the average stress in the various lattice bars of the columns. Tests 14 and 15 were tests on the lattice bars only.

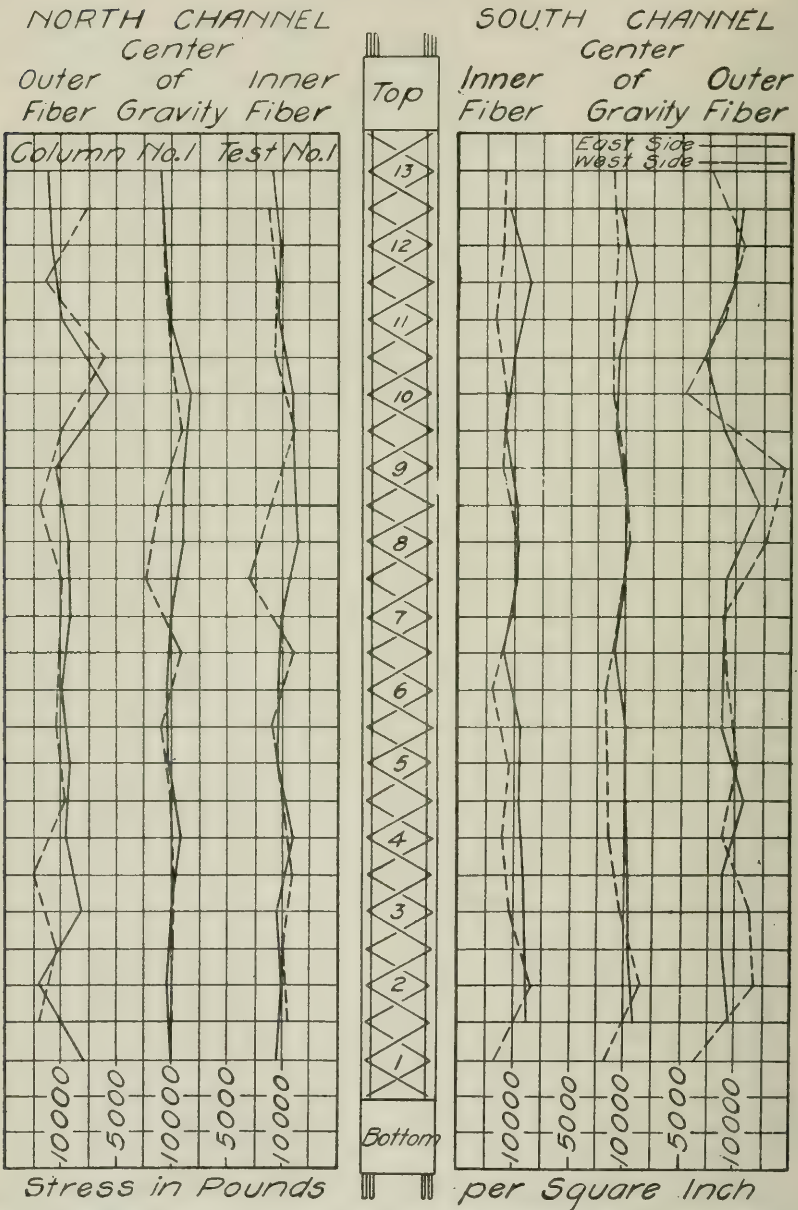

FIG. 8. STRESS DISTRIBUTION IN CHANNELS OF COLUMN NO. 1, TEST NO.1.

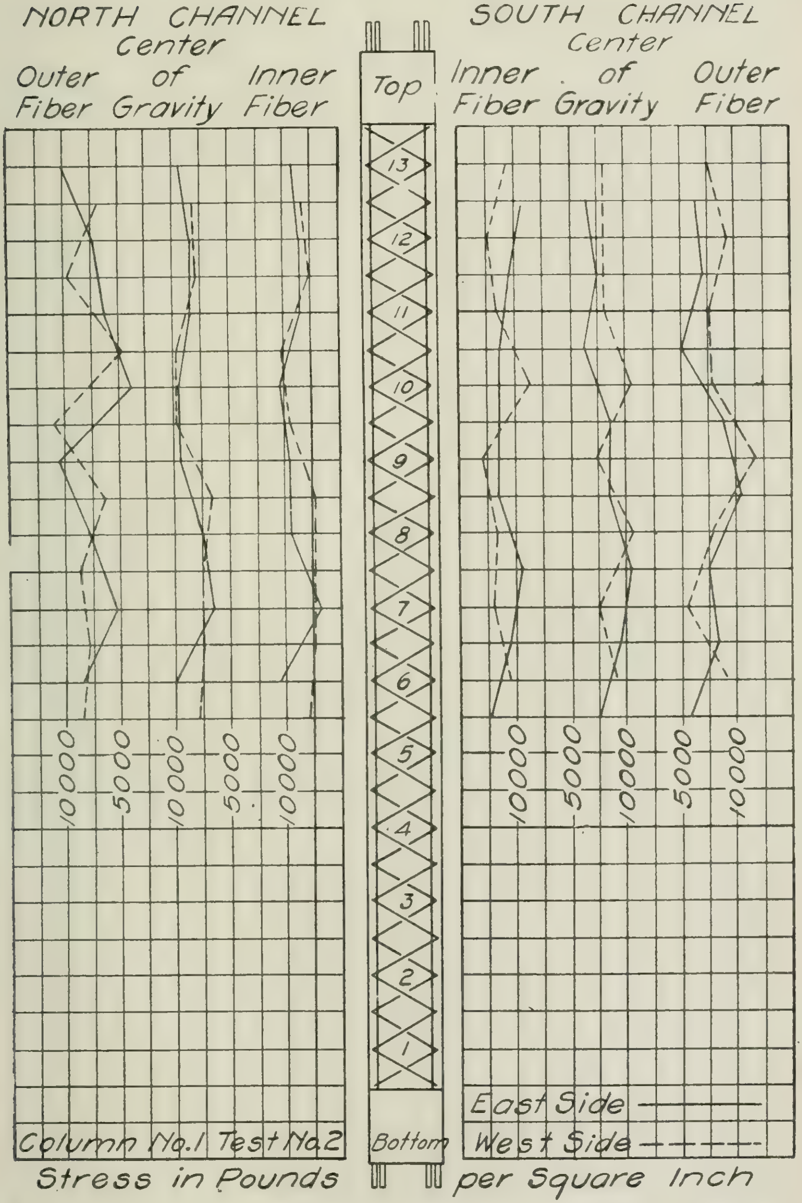

FIG. 9. STRESS DISTRIBUTION IN CHANNELS OF COLUMN NO. 1, TEST NO. 2.

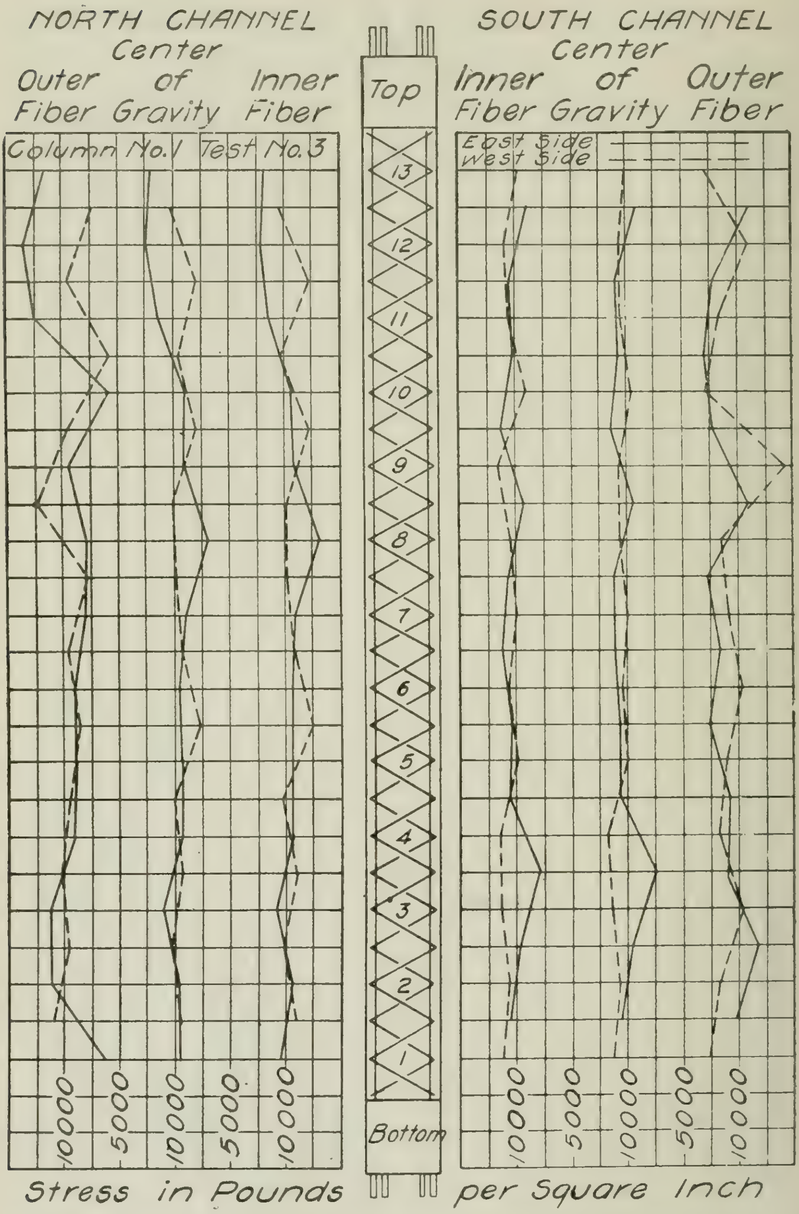

FIG. 10. STRESS DISTRIBUTION IN CHANNELS OF COLUMN NO. 1, TEST NO. 3.

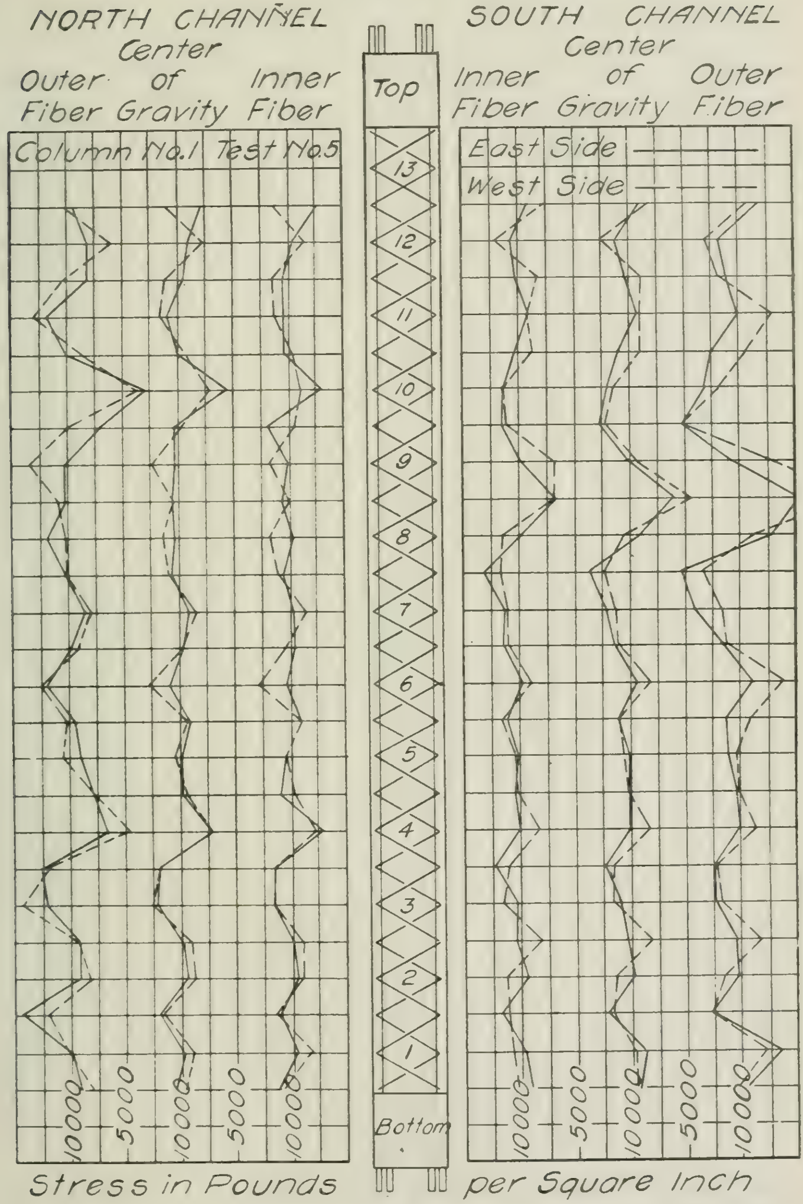

FIG. 11. STRESS DISTRIBUTION IN CHANNELS OF COLUMN NO. 1, TEST NO. 5.

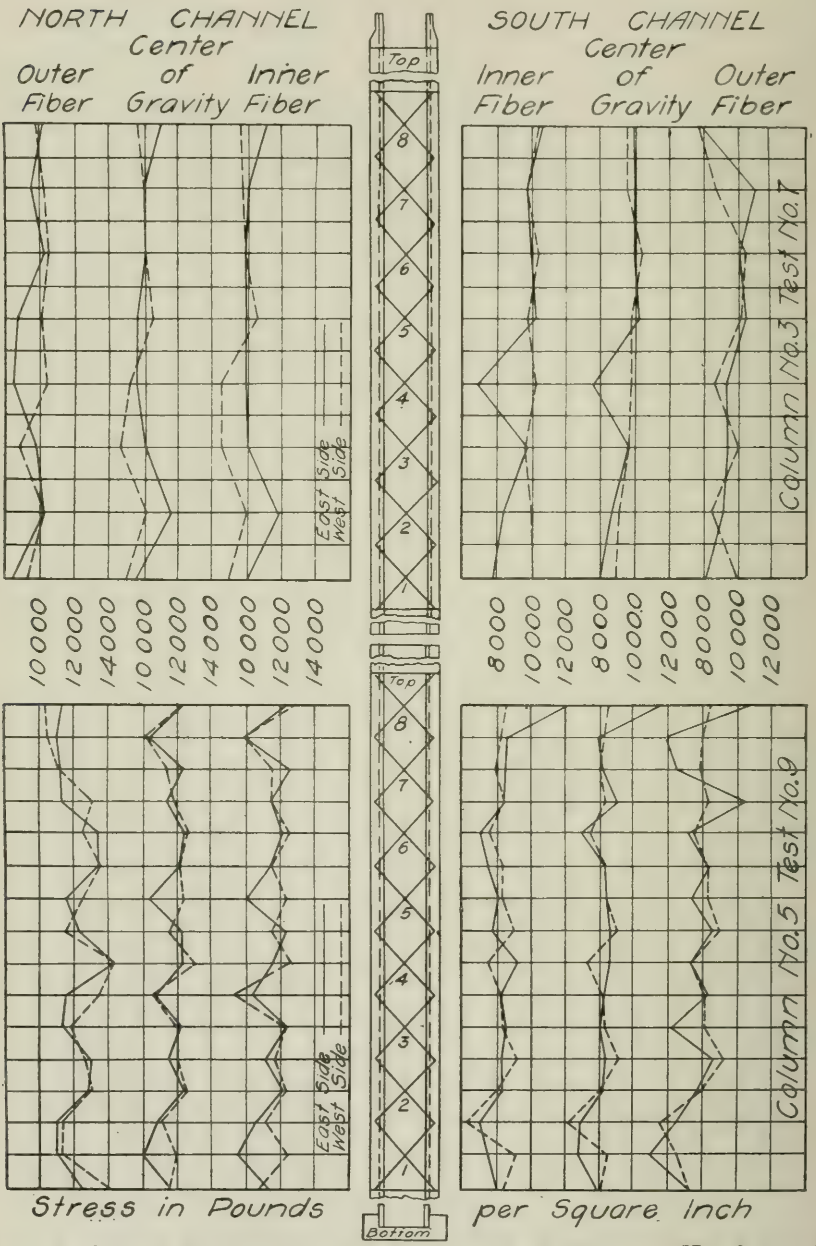

FIG. 12. STRESS DISTRIBUTION IN CHANNELS OF COLUMNS NO. 3 AND 5.

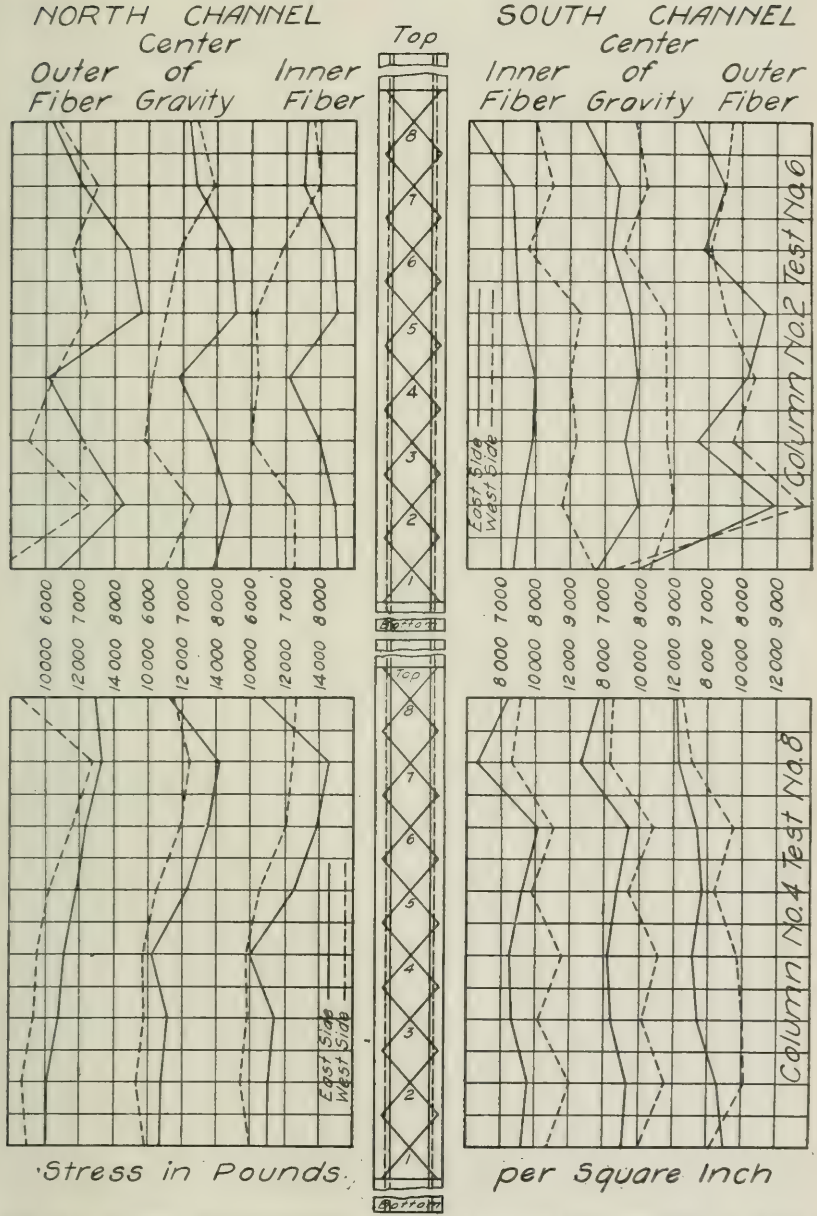

FIG. 13. STRESS DISTRIBUTION IN CHANNELS OF COLUMNS NO. 2 AND 4.

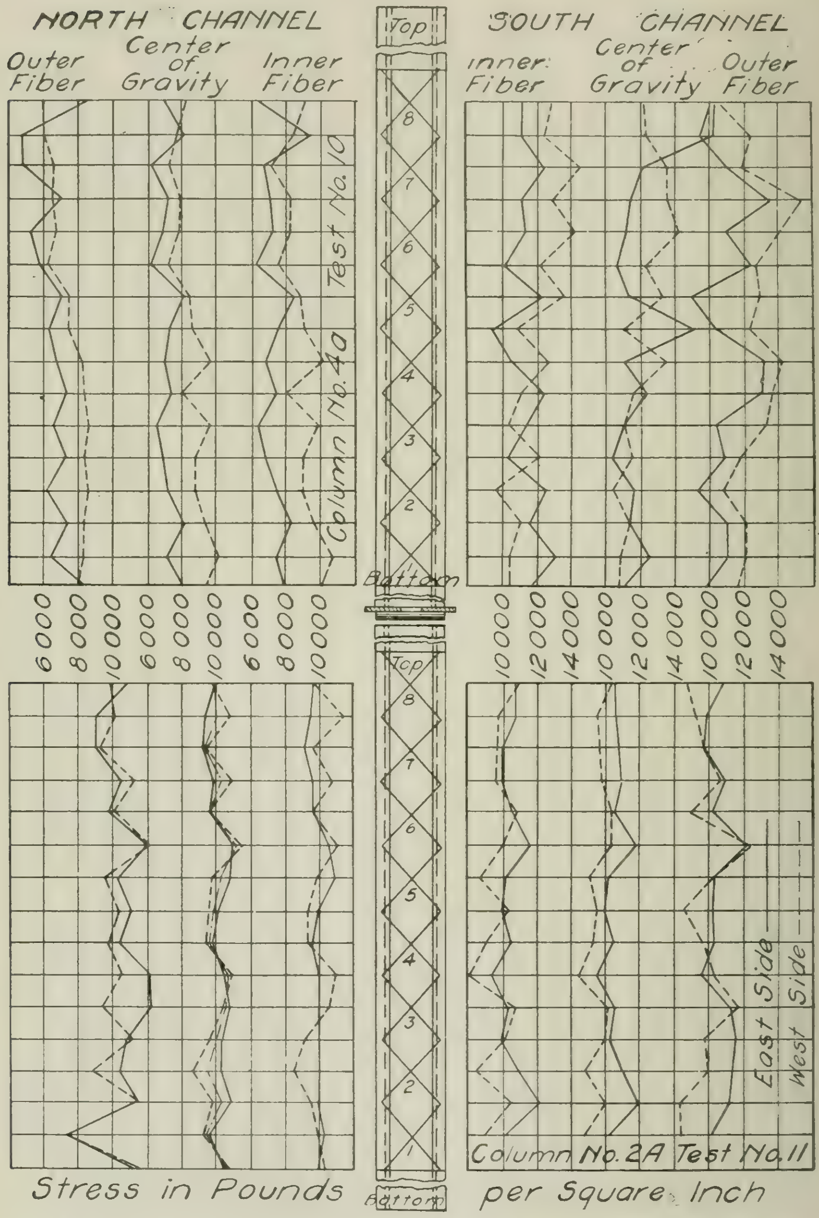

FIG. 14. STRESS DISTRIBUTION IN CHANNELS OF COLUMNS NO. 2a AND 4a.

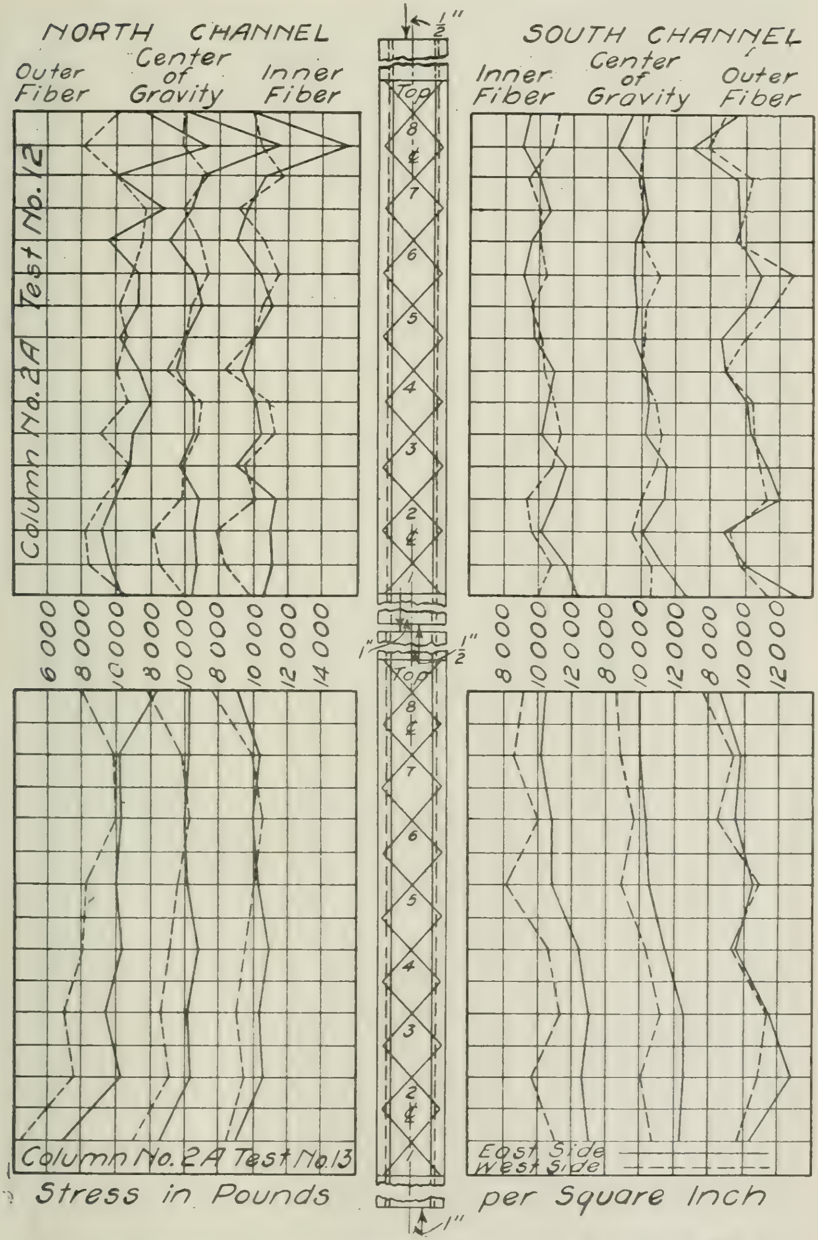

FIG. 15. STRESS DISTRIBUTION IN CHANNELS OF COLUMN NO. 2a.

The distribution of stress over the cross-section of the bar is discussed in another place. The average stresses in the lattice bars are computed from the observed deformation, using a modulus of

TABLE 4.

MAXIMUM OBSERVED FIBER STRESSES IN FLANGE MEMBERS OF COLUMNS.

Col. No.	Test No.	Feature of Lacing	Method of Loading	Excess of Maximum Fiber Stress over Average Stress per cent Highest five values
1	1	$1\frac{1}{4} \times \frac{7}{16}$ in. bolted	Central	42, 41, 39, 31, 23
1	2	"	Slightly eccentric	68, 64, 50, 49, 35
1	3	"	"	50, 41, 35, 32, 19
1	4	$1 \times \frac{1}{4}$ in. bolted	Central	35, 29, 28, 27, 26
1	5	$1 \times \frac{1}{4}$ in.	"	67, 55, 49, 29, 27
2	6		"	31, 23, 23, 21, 17
3	7		"	20, 17, 12, 11, 9
4	8		"	41, 29, 24, 22, 19
5	9		"	43, 43, 38, 35, 35
4a	10		"	53, 49, 42, 40, 37
2a	11		"	21, 16, 13, 12, 11
2a	12		Oblique (Fig. 6) Arm 1 in.	42, 42, 24, 23, 20
2a	13		Oblique (Fig. 6) Arm 2 in.	35, 34, 22, 21, 21

TABLE 5.

TOTAL STRESS IN POUNDS ON LATTICE BARS UNDER LOAD ON COLUMNS OF 10 000 LB. PER SQ. IN.

c denotes compressive stress; t, tensile stress.

Lattice Bar	Test 5		Test 14		Test 15	
	Front	Back	Front	Back	Front	Back
1	400c	400c	300t	400t	——	——
2	100t	600t	1600t	400c	——	——
3	0	600c	800c	400t	——	——
4	100t	400t	300t	100c	——	——
5	100c	100c	——	——	——	——
6	200t	300t	——	——	——	——
7	100c	200c	——	——	——	——
8	200t	200t	——	——	——	——
9	0	300c	——	——	——	——
10	0	200t	——	——	——	——
11	100c	300c	——	——	——	——
12	0	100t	——	——	——	——
13	100c	200c	800c	0	——	——
14	100t	200t	900t	900t	2500t	1600c
15	0	300c	200c	1000t	2100c	——
16	0	400t	800t	0	1600t	200c
17	200c	200c	500c	300t	1900c	——
18	200t	100t	700t	1000t	700t	1100t
19	500c	200c	500c	200t	1500c	——
20	200t	300t	800c	200t	1400t	700t
21	0	600c	800c	600t	1500c	0
22	100c	2000t	0	200t	700t	300t
23	200t	900c	300c	800c	1300c	——
24	200c	800t	200t	800t	600t	400c
25	200t	800c	0	0	2700c	——
26	200c	700t	400t	300c	400t	400c

TABLE 5—(*Continued*).

TOTAL STRESS IN POUNDS ON LATTICE BARS UNDER LOAD ON COLUMNS OF 10 000 LB. PER SQ. IN.

Lattice Bar	Front Side		Back Side	
	Under	Over	Under	Over
	Column 2a.	Test 11.	Column 2a.	Test 11.
1	700c	700c	1300c	100c
2	100c	100t	200t	200t
3	3000t	0	1000t	0
4	100c	100c	800c	200c
5	3000t	0	800c	300c
6	200t	200c	0	300c
7	3700t	0	200t	200c
8	0	800c	800c	300c
	Column 2a.	Test 12.	Column 2a.	Test 12.
1	1500c	2100t	200c	200c
2	200c	400t	2300t	200c
3	800t	200t	2750t	400c
4	700c	500t	2750t	300c
5	1600t	200t	2750t	300c
6	0	0	2800t	800c
7	1400t	800c	4100t	300c
8	100t	800c	300t	800c
	Column 2a.	Test 13.	Column 2a.	Test 13.
1	1000c	700t	800t	500c
2	500c	700t	2650t	400c
3	700c	900t	2750t	300c
4	500c	1000t	2100t	200t
5	800c	600t	3150t	1000c
6	1000c	700t	4100t	700c
7	700c	900t	1500t	400c
8	1600c	200c	2000t	1400c

elasticity of 28 000 000 lb. per sq. in. for the steel column and 26 000 000 lb. per sq. in. for the wrought-iron columns. As might be expected, from the irregular variation of stress along the flange members of the columns, the stress in the lattice bars was found to vary greatly.

Table 6 gives the largest stresses observed and the corresponding transverse shear. The transverse shear given in this table is that which would cause a stress in the lattice bars equal to the maximum stress observed in any lattice bar, and was computed by doubling the transverse component of the maximum load observed on a lattice bar. In the case of obliquely loaded columns, the transverse component of the load was computed on the assumption that the load was applied through the center of the bearing blocks. This transverse component was then subtracted from the amount of shear which has been calculated from the def-

TABLE 6.

Maximum Observed Average Stress in Lattice Bars of Columns No. 1 and 2a.

Column number	1	1	1	2a	2a	2a
Test number	5	14	15	11	12	13
Method of loading	Central	Central	Oblique (Fig. 6) Arm 4 in.	Central	Oblique (Fig. 6) Arm 1 in.	Oblique (Fig. 6) Arm 2 in.
Total load, pounds	187 600	187 600	187 600	176 400	176 400	176 400
Lacing	Single 63° 30′ with axis, 1×¼ riveted	Single 63° 30′ with axis, 1¼×$\frac{7}{16}$ riveted	Single 63° 30′ with axis, 1¼×$\frac{7}{16}$ riveted	Double 45° 2½×⅜ riveted	Double 45° 2½×⅜ riveted	Double 45° 2½×⅜ riveted
Maximum observed average stress in lattice bar, lb. per sq. in	8200	3000	4900	3900	4350	4350
Corresponding total stress in bar, pounds	2000	1600	2700	3700	4100	4100
Corresponding transverse shear in column, pounds	3700	2900	4800	5200	5800	5800
Shear due to known eccentricity of load, pounds	0	0	3000	0	1000	2000
Transverse shear in column due to nominal central load, pounds	3700	2900	1800	5200	4800	3800
Ratio of shear to compression load	.020	.016	.009	.029	.027	.021
Next highest observed values of ratio of shear to compressive load	.009 .008 .008 .007	.010 .010 .009 .009	.009 .007 .006 .006	.024 .023 .010 .008	.019 .018 .018 .018	.016 .014 .014 .011

ormation of the lattice bars as before noted, and the remainder has been tabulated under the heading "Transverse Shear in Column due to Nominal Central Load".

The failure of Column No. 1 by buckling of the lattice bars, as described elsewhere, gives further information along this line. Tests to destruction under compression had previously been made on lattice bars like those used in this column, and the results, in the absence of other data, may be useful in estimating the load carried by the lattice bars at failure. Under conditions of loading similar to the conditions in the column lattice bars, these sample bars failed under an average load of 2100 lb. Assuming that the bar in this column which first failed was carrying 2100 lb. when failure occurred, the transverse shear in the column may be computed. The following tabulated statement gives the conditions of this test, and may be regarded as supplementary to Table 6.

Column No.	Compressive Load in Pounds	Lacing	Manner of Loading	Probable Maximum Load on Lattice Bar in Pounds	Corresponding Shear in Column in Pounds	Ratio of Transverse Shear to Compression Load
1	150 000	Single 63° 30′. 1 x ¼ in. riveted	Very slight obliquity	2100	3760	0.0251

14. *Tests to Failure of Wrought-iron Columns.*—After the wrought-iron bridge posts had been tested for stress distribution under working loads, they were loaded to failure. Deformations were measured in the flange members of that part of the column on which the previous test had given the heaviest stress. Table 7 gives the result of the tests to failure. For all the tests of wrought-iron bridge posts, whether loaded centrally or eccentrically, the failures were very gradual. Final failure occurred near the middle or at the end. In the former case, high stresses in one channel had been shown by the deformation measurements at working loads. In the latter case, a bending in one channel at working loads was noted by the instruments at the panel nearest the end of the column. In two of the three columns in which failure took place in the end of the column, as the instruments did not show over-stress in the laced portion of the column, the injured ends were removed, new end connections were put on, and the columns were retested as No. 2a and 4a.

15. *Tests to Failure with Column No. 1.*—Two tests to failure were obtained with Column No. 1. In the first test, the lattice

bars failed by buckling suddenly and without warning. As tested, the column was fitted with the light lattice bars (1 x $\frac{1}{4}$ in.) riveted in place. The test had in view the trial for stress distribution under a slight obliquity, which was not carefully determined. No measuring instruments were in place. A preliminary load was being applied. When the load reached 150 000 lb. (8060 lb. per sq. in. of cross-section), the alternate lattice bars in the upper half of the column buckled. A failure of this kind was quite unexpected at such a low load. Although an observer was watching the column, the failure was so sudden that he was unable to follow the movement of the parts. In this respect it was quite in contrast to the failure of the other columns. The machine was at once stopped. Little damage was done to the column, except to the lacing bars. The webs were easily straightened, new lacing bars put on, and the column was used in another test.

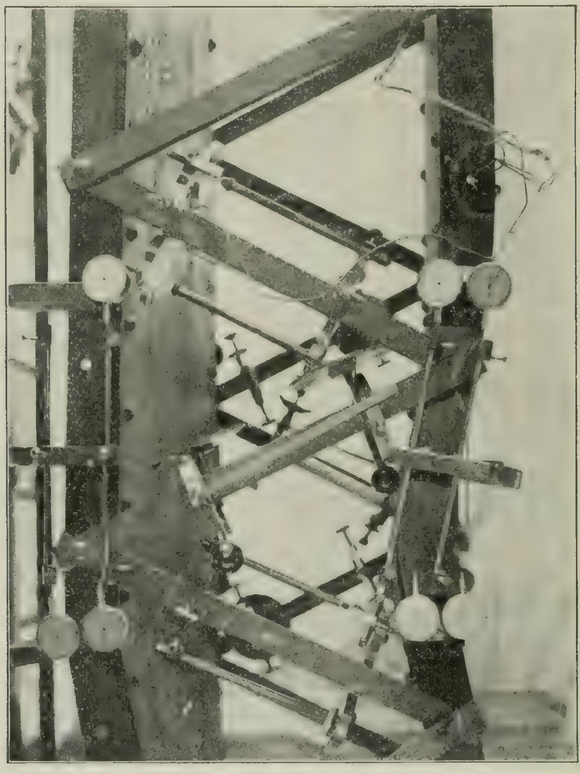

FIG. 16. COLUMN NO. 1 AFTER FAILURE.

TABLE 7.

RESULTS OF TESTS TO FAILURE.

Column No.	1	1	2	3	4	5	2a	4a
Test No.		17	6	7	8	9	13	10
Material	Steel	Steel	W. I.	W. I.	W. I.	W. I.	W I.	W. I.
Method of loading	Very slight obliquity	Central	Central	Central	Central	Central	2-in. oblique (Fig. 6)	Central
Load at failure, pounds	150 000	440 000	466 000	480 000	452 000	492 000	475 000	475 000
Average stress at failure, lb per sq. in.	8 060	23 450	26 400	27 200	25 700	27 900	26 900	26 900
Average stress at failure in tests of short pieces of flange members, lb. per sq. in.	—	—	36 800	36 800	36 800	36 800	36 800	36 800
Percentage of excess of ultimate strength of short pieces over column strength	—	—	39.5	35.5	43.5	32.0	37.0	37 0
Load at first sign of yielding, pounds	150 000	225 100	317 000	264 000	256 000	264 000	—	—
Average stress at first sign of yielding, lb. per sq. in.	8 060	12 000	18 000	15 000	14 500	15 000	—	—
Method of failure and remarks	Very sudden buckling of lacing bars in upper half	Sudden buckling of flange between adjacent lacing bars	End failed	End failed	End failed	Bowed at middle in plane perpendicular to lacing	Buckled near bottom in plane parallel to lacing	Bowed at middle in plane perpendicular to lacing

The column having been riveted up with heavier lattice bars ($1\frac{1}{4} \times \frac{7}{16}$ in.), it was next subjected to several tests for stress distribution and was finally loaded to failure with a central load. Measuring instruments were attached to flanges and lattice bars near that part of the column in which, from the results of previous tests, the greatest stress was expected. Fig. 16 shows the attachment of instruments to the columns. Failure occurred under a load of 440 000 lb. (23 450 lb. per sq. in. of section); it was caused by the local buckling or "wrinkling" of the north flange in panel 8, the panel in which the greatest stress had been found in Test No. 5. The failure of the column was slower than that of the preceding test in which the lattice bars buckled, but it was much more sudden than were the failures of the wrought-iron columns. One lattice bar on each side was buckled by the crippling of the channel member. The measuring instruments attached to the web at panel 8 showed from the first of the test that there was a very large stress at that point.

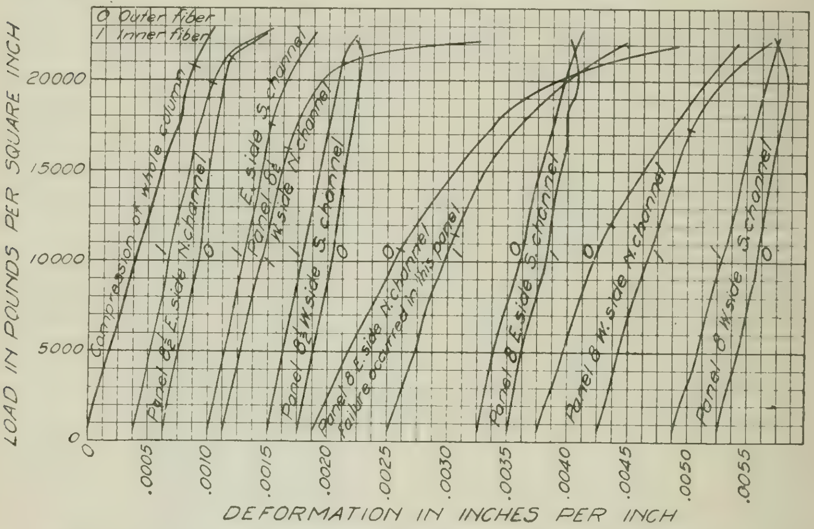

FIG. 17. LOAD-DEFORMATION CURVES OF TESTS TO FAILURE OF COLUMN NO. 1.

Fig. 17 shows the stress-deformation curve as taken at various points. The uneven distribution of stress is clearly shown, and the first sign of approaching failure is seen at about 12 000 lb. per sq. in. Fig. 16 shows the column after failure.

The low average stress at failure in Column No. 1 should be noted, and also the manner of failure. There is a sharp contrast between the gradual bowing of the stocky columns tested and the sudden wrinkling collapse of the flimsy steel column.

16. *Cross-bending Test of Columns.*—Cross-bending tests were made on one of the wrought-iron columns and on Column No. 1. The tests were made in an Olsen 200 000-lb. testing machine fitted for testing beams 20 ft. long. The columns were supported at the ends and loaded at the center with a light transverse load. The column was placed first with the plane of the lacing perpendicular to the load, and then with the plane of the lacing parallel to the load. The lattice bars used in the tests of Column No. 1 were $1\frac{1}{4}$ x $\frac{7}{16}$ in. in cross-section; in one test they were bolted in place and in another they were riveted. The deflection at various points along the beam was measured with Ames test gauges, and the actual curve assumed by the column under transverse load

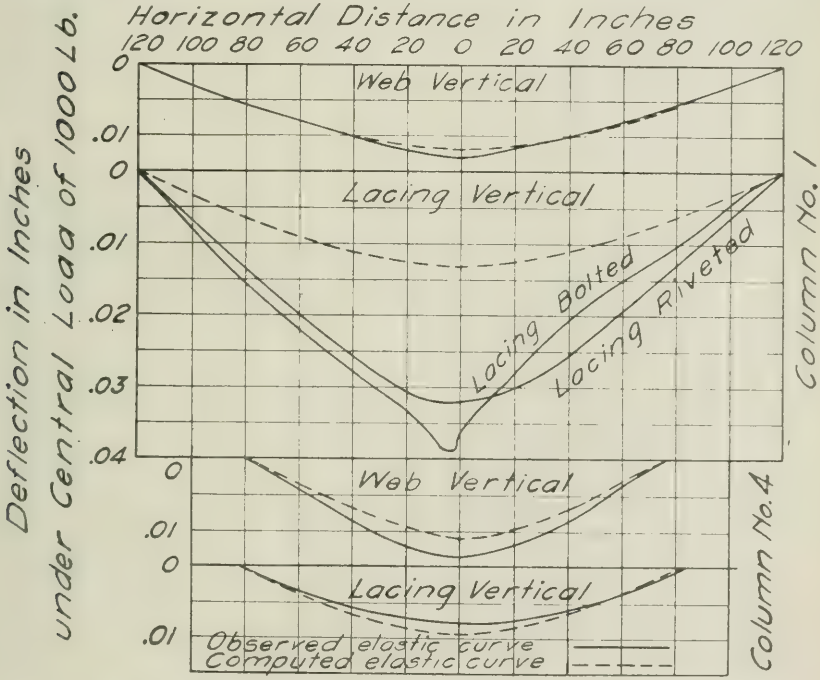

FIG. 18. DEFLECTION OF COLUMNS UNDER CROSS BENDING.

was thus determined. The theoretical elastic curve was computed from the common theory of flexure, not counting the lattice bars in the calculation of the moment of inertia. Fig. 6 (p. 13) shows the deflectometers and extensometers on Column No. 1 under the cross-bending test. Fig. 18 shows the deflection curves given by the columns under transverse load and also the computed elastic curves.

It will be noted that when tested with the lacing vertical, Column No. 1 shows much greater deflection than that computed from the usual beam formula, while the stiffer wrought-iron column shows a much closer agreement with the curve, the heavy lacing apparently adding stiffness.

III. FIELD TESTS OF COLUMNS.

17. *Description of Bridge.*—The field tests of columns were made on compression members in a bridge which spans the Sangamon river near White Heath, Illinois, on the line of the Illinois Central Railroad between Champaign and Clinton, Illinois. This bridge is an eight-panel, single-track, Pratt truss, having a span of 158 ft. 6 in. Fig. 19 gives a diagram of the bridge, and the frontispiece is from a photograph of the bridge under test.

18. *Members Investigated.*—The members in which stresses were measured were Post U_2L_2 South, U_3L_3 South, U_3L_3 North,

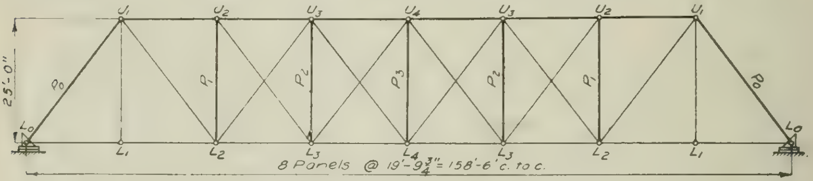

FIG 19. DIAGRAM OF WHITE HEATH BRIDGE.

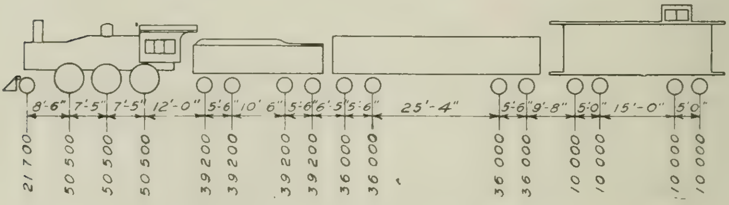

FIG. 20 DIAGRAM OF TEST TRAIN.

and Upper Chord U_3U_4 South. The location of these members is shown in the bridge diagram, Fig. 19. The upper chord was made up of two built-up channels with a cover plate on top and double lacing across the bottom. The end of each upper chord was riveted to a connection plate to which was riveted the adjacent end of the next upper chord and also the post under the junction of the chords. The posts were made up of two steel channels double laced, and the floor beams were directly riveted to the posts. The upper ends were riveted to a connection plate as noted above and the lower ends carried pins to which the lower chord members (eyebars) were attached. Fig. 21 shows in detail a post and upper chord.

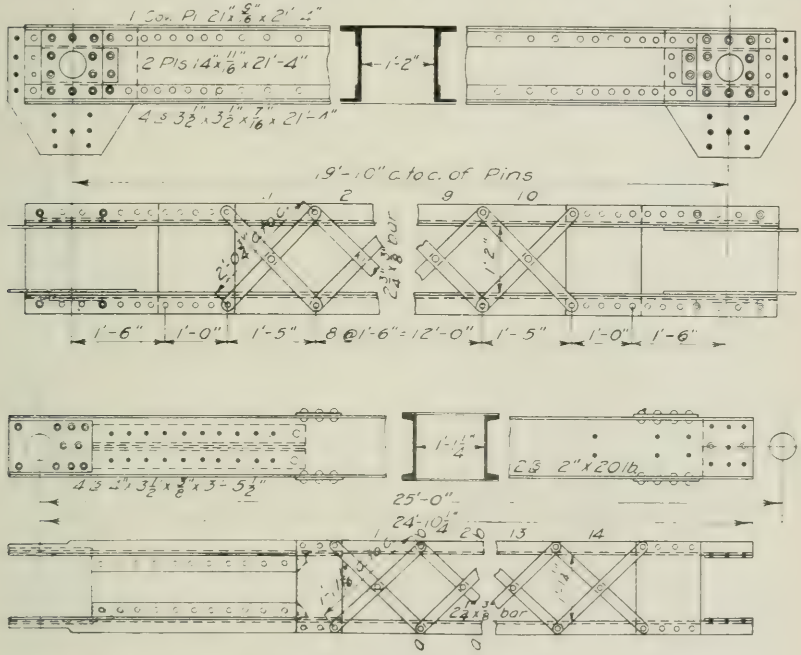

Fig. 21. Upper Chord and Post of White Heath Bridge.

19. *Application of Load.*—The test load applied to the bridge consisted of a mogul locomotive and tender, I. C. R. R. No. 555, followed by a loaded coal car and a caboose. Fig. 20 shows the test train, with dimensions and weights. This train was furnished through the courtesy of the railroad company.

20. *Measurement of Deformation.*—Ames test gauges were used as extensometers, and the method of attachment was the same as in the laboratory tests of columns. The method of reduction of instrument readings to stresses at the extreme fibers of members was also the same.

TABLE 8.

STRESSES IN POSTS OF WHITE HEATH BRIDGE.

Panel	North Channel						South Channel					
	East Side			West Side			East Side			West Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
Post U_3L_3 South.												
1*	5 000	5 300	5 400	2 600	2 700	2 700	4 900	5 000	5 000	2 300	2 500	2 600
2	3 400	3 500	3 500	1 900	1 600	1 500	3 300	3 400	3 400	1 600	1 800	1 800
3	3 500	3 800	4 000	1 800	1 900	2 000	2 600	2 900	3 100	2 600	2 200	2 100
4	3 700	3 400	3 300	2 800	3 000	3 000	1 600	3 100	3 600	2 400	2 800	2 900
5	3 500	3 900	4 000	2 900	2 900	2 900	2 800	3 000	3 100	2 200	2 600	2 800
6	3 600	3 600	3 600	3 400	3 800	3 900	3 400	3 400	3 400	4 100	3 400	3 200
7	2 600	3 200	3 400	3 300	3 100	3 000	2 400	3 000	3 300	2 600	2 700	2 800
8	3 300	3 200	3 200	3 900	3 600	3 500	3 600	3 400	3 300	3 700	3 900	3 900
9	3 200	3 100	3 000	3 600	3 300	3 200	1 700	2 500	2 800	2 900	3 300	3 400
10	2 800	2 700	2 700	3 100	3 300	3 300	2 700	2 400	2 300	3 300	3 700	3 900
11	3 300	2 900	2 800	4 500	3 400	3 100	2 900	2 000	1 700	3 500	3 900	4 100
12	1 400	2 000	2 300	3 100	3 200	3 200	1 800	1 800	1 800	4 800	4 700	4 600
13	1 300	1 500	1 500	2 800	2 700	2 600	2 600	2 900	3 100	5 200	4 900	4 800
Post U_3L_3 North.												
1	4 900	4 900	4 900	2 600	2 500	2 500	4 800	4 900	4 900	2 100	2 700	2 800
1½	4 800	4 700	4 700	2 900	2 800	2 700	3 100	4 900	5 700	900	1 500	1 700
2	4 800	4 400	4 300	2 600	2 500	2 500	4 900	4 700	4 600	2 700	1 700	1 300
2½	4 000	3 900	3 900	2 700	2 800	2 900	4 300	3 700	3 500	2 300	1 800	1 600
3	3 900	4 200	4 300	2 800	2 900	2 900	......	....	....	....	....	....
3½	3 900	3 900	4 000	2 400	2 500	2 500	3 200	3 800	4 100	2 400	2 500	2 500
4	3 400	4 600	5 000	2 700	2 700	2 700	3 900	3 700	3 700	3 500	3 200	3 100
4½	3 800	3 400	3 200	2 500	2 300	2 200	3 500	3 500	3 400	3 100	3 000	3 000
5	3 900	3 700	3 600	3 700	3 700	3 700	3 100	3 600	3 800	1 400	2 100	2 400
5½	4 100	3 600	3 400	4 000	3 400	3 200	3 500	3 900	4 100	3 500	2 900	2 800
6	3 600	3 200	3 100	3 400	3 300	3 200	3 700	3 500	3 400	3 900	3 600	3 500
6½	3 300	3 300	3 300	3 600	3 500	3 500	4 500	4 700	4 800	2 000	2 400	2 600

*No explanation for the high values in Panel 1 has been found. Five determinations of stress were made, including the removal and re-attachment of instruments.

21. *Routine of Tests.*—As in the laboratory tests, the stress distribution in the channels and the lattice bars was studied. The method of procedure was as follows. Instruments were placed on some portion of the column to measure the deformation over a short gauge length, and a reading was taken. The test train was then run upon the bridge to a given position (one approxi-

mating the maximum load on the member under test), and the instruments were read again. The train was then run off the bridge, and the instruments were again read. This procedure was repeated several times, at least three applications of the load being made and frequently several more. The instruments were then moved to another part of the column, and that part was tested. Observations were made on both flange members and lattice bars. The tests covered a period of eight days. The weather was ideal with the exception of one day.

TABLE 9.

STRESSES IN UPPER CHORD OF WHITE HEATH BRIDGE.

Stresses are given in lb. per sq. in.

Panel	Lower Side (Laced)				Upper Side (Cover-plate)				
	North Channel		South Channel		Distance from End inches	North Edge	Over North Web Plate	Over South Web Plate	South Edge
	Outer Fiber	Inner Fiber	Outer Fiber	Inner Fiber					
1	4 300	3 900	5 000	5 500	33	5 500	6 000	5 200	5 700
2	4 900	4 300	4 500	4 800	57	....	....	5 200	5 500
3	2 800	5 500	3 400	4 500	81	5 200	5 400	5 900	5 300
4	2 800	5 100	4 200	5 300	105	5 000	6 100	5 700	6 000
5	5 700	5 400	3 900	4 800	129	4 800	5 900	5 900	5 900
6	5 500	4 800	5 100	4 200	153	5 400	5 700	5 500	5 600
7	5 900	4 700	3 400	3 600	177	5 000	5 000	5 700	5 600
8	6 200	5 300	3 300	4 400	....	....	....	....	....
9	6 000	5 300	4 700	3 800	....	....	....	....	....
10	5 900	5 100	4 400	4 900	....	....	....	....	....

22. *Results of Tests for Stress Distribution in Channels.*—Table 8 gives the results of the tests to determine the stress distribution and variation in the channels of the bridge posts, and Table 9 gives those for the top chord. The stresses given were calculated from the observed deformations, using a modulus of elasticity of 30 000 000 lb. per sq. in. The conditions of measurement of deformation were much the same as in the laboratory tests. The stress noted is the average stress over a space of 4½ in. on either side of the point indicated.

Fig. 22 and 23 show graphically the stress distribution and variations. In these figures the full lines give the stresses at the west side (front), and the dotted lines the stresses at the east side (back).

In Table 10 (p. 44) are given a number of the highest observed fiber stresses. The excess of the maximum fiber stress is given

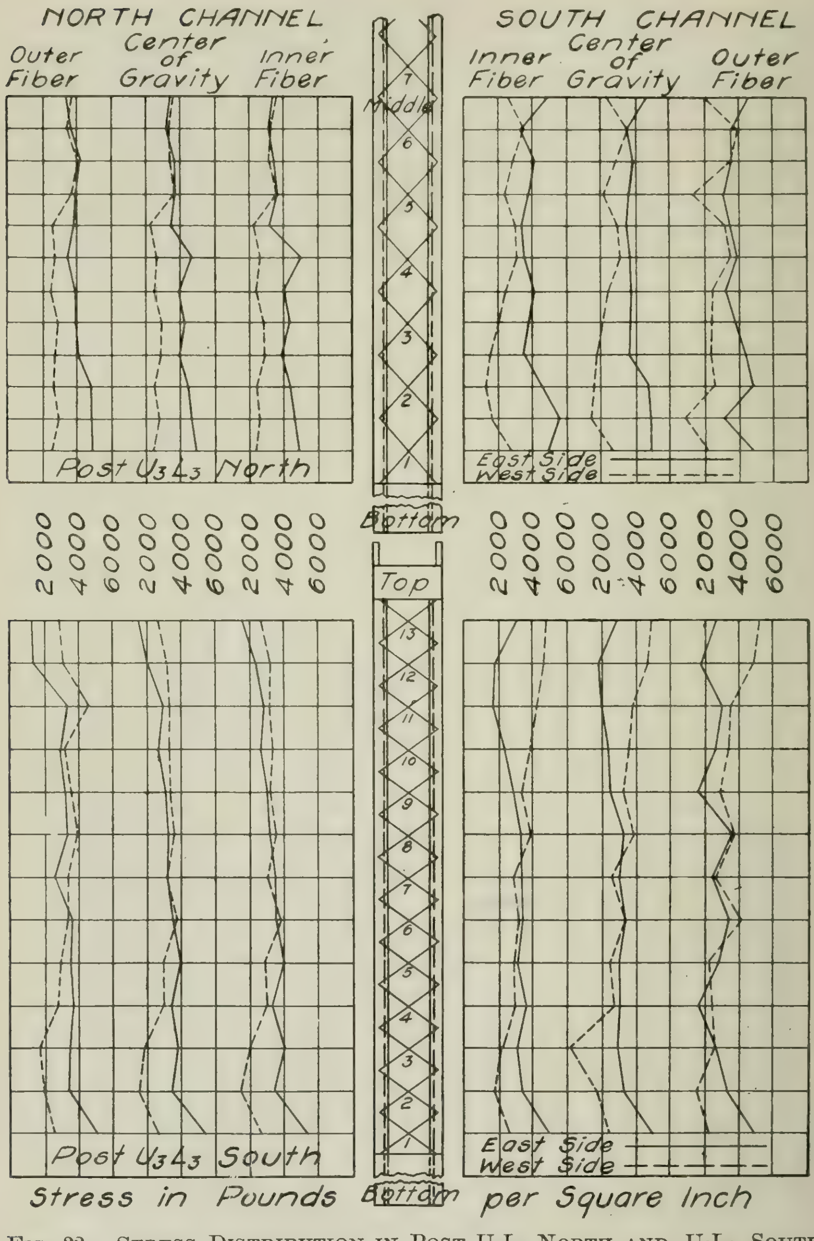

FIG. 22. STRESS DISTRIBUTION IN POST U_3L_3 NORTH AND U_3L_3 SOUTH OF WHITE HEATH BRIDGE.

as a percentage of the average stress. At most sections the maximum stress was in the outer fiber of the channel, but in some cases it was found at the inner fiber.

In the tests of the bridge posts an attempt was made to determine the stresses in a few of the lattice bars. These stresses were very small, and the precision of the extensometer was not sufficient to measure them with any great degree of accuracy.

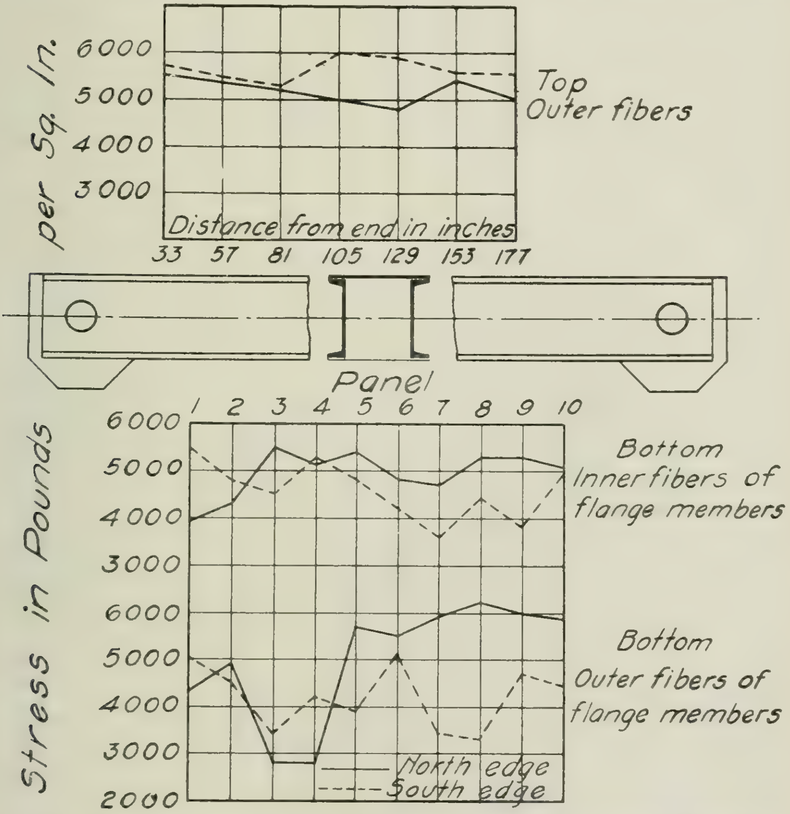

FIG. 23. STRESS DISTRIBUTION IN UPPER CHORD U_3U_4 OF WHITE HEATH BRIDGE.

It should be noted that the lacing of the posts in this bridge was double, and the bars were riveted together at their intersection. In several cases it was found that a lattice bar under load bent in the shape of a very flat S-curve, the point of attachment to another lacing bar, at the middle, being a point of inflection.

23. *Special Tests on Bridge Columns.*—Tests were made on the batten plates at the top of one of the posts, and under load a slight bending of the plates between channels was found. The bending took place in a horizontal plane.

TABLE 10.

MAXIMUM OBSERVED FIBER STRESS IN FLANGE MEMBERS OF COLUMNS IN WHITE HEATH BRIDGE.

Column number	$U_3 L_3$ South	$U_3 L_3$ North	$U_3 U_4$ South
Test number	F 1	F 2	F 3
Lacing	Double 45° riveted at crossing	Double 45° riveted at crossing	Cover plate on top. Double 45° on bottom
Maximum observed compressive stress in an extreme fiber, lb. per sq. in.	5200	5700	6200
Excess maximum observed stress over average, per cent. Highest five values	73* 63 60 57 47	64 48 41 31 31	20 19 17 17 17

* No values from Panel 1 have been included in this table as no explanation is known of the high stresses indicated in that panel.

In one post the change of stress was observed as the locomotive and train moved across the bridge. Extensometers were placed at aa, bb (Fig. 21), and on the floor beams, and the changes in reading were noted as the train moved across the bridge. In the inner channel of the post, tension was set up as the locomotive came opposite the post. The maximum amount of tension observed in the inner channel when the locomotive was opposite the post was about three-quarters of the compression in the outer channel.

IV. TESTS OF LATTICE BARS, SMALL COLUMNS, AND COLUMN MATERIAL.

24. *Compression Tests of Lattice Bars.*—Many of the lattice bars in a column, as they transmit stress from one flange member of the column to the other, are under compression. To study the action of lattice bars under compression, a series of tests on single lattice bars was made. Fig. 24 shows the arrangement of the apparatus. The lattice bar was tightly bolted to the blocks, B_1 and B_2. The upper block, B_1, was fastened to the cross-head of a testing machine, and the block B_2 was pressed against the

weighing table of the testing machine. A spherical-seated bearing block was used, to insure an even bearing. Ames test gauges, E, mounted on suitable frames, were attached to the lattice bar over a short gauged length. From the readings of these gauges, the deformation of the extreme fiber of the bar was computed.

In this test of lattice bars, the load was applied with an eccentricity approaching that to be expected in a column for the lattice bars which are next to the flange member (here designated "under" bars). The lattice bars outside of these "under" bars are here designated "over" bars. The stress distribution across the section of the "over" bars, which are under compression, is probably more uneven than the stress distribution found in these tests. However, these tests give some idea of the relative behavior of lattice bars of various proportions, and of the large eccentricity of loading of all lattice bars.

Lattice bars of the following cross-sections were tested: Flat bars $1\frac{1}{2}$ x $\frac{1}{4}$ in., 1 x $\frac{3}{8}$ in., $\frac{7}{8}$ x $\frac{7}{16}$ in.; angles $1\frac{1}{2}$ x $1\frac{1}{2}$ x $\frac{1}{8}$ in.; channels $1\frac{1}{2}$ x $\frac{3}{4}$ x $\frac{1}{8}$ in. Several channel and angle lattice bars were tested with ends flattened and ribs turned inward, to minimize the eccentricity of loading. Bars of the following lengths between centers of rivet holes were tested: $8\frac{1}{2}$ in., $13\frac{1}{2}$ in., and 20 in. The rivet holes were $\frac{1}{2}$ in. in diameter. All bars were tested in a Philadelphia Machine Tool Company's 100 000-lb. testing machine, and loads and extensometer readings were taken to failure.

Observations were also made on the behavior of a lattice bar in a column under load, with a view to determine the distribution of stress over the section. For this purpose Column No. 1 was loaded obliquely. The instruments were placed on an "over" bar

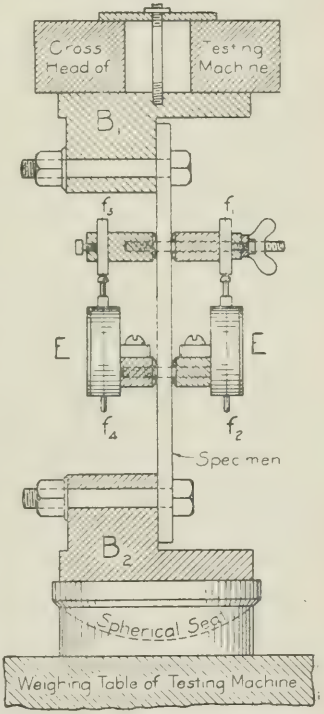

FIG. 24. ARRANGEMENT OF APPARATUS IN COMPRESSION TESTS OF LATTICE BARS.

which had been found to carry a high compressive stress, and readings were taken to determine the distribution of stress across the section.

When Column No. 1 was under cross-bending test, observations were made to determine the stresses transmitted by lattice bars and their distribution over the section of the bars. Extensometers were placed successively on most bars under compression on one-half of the column, and on some bars which were under tension. In both of these tests the bars were $1\frac{1}{4}$ x $\frac{7}{16}$ in., and were riveted.

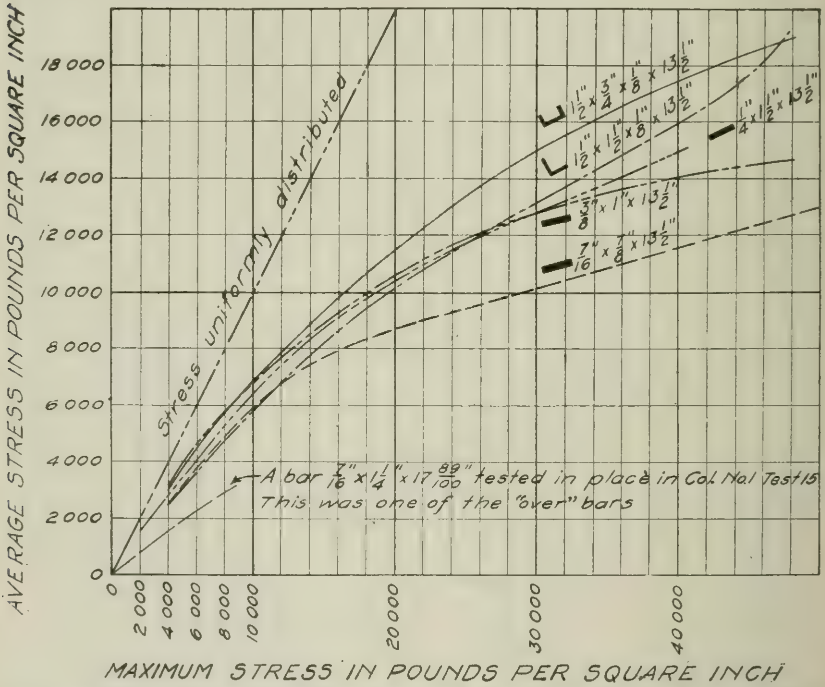

FIG. 25. FIBER STRESS IN COMPRESSION TESTS OF LATTICE BARS, ENDS HELD AS IN FIG. 24.

25. *Results of Tests of Lattice Bars.*—The results of the tests of single lattice bars are given in Fig. 25 and 26, and in Tables 11 and 12. Fig. 25 shows the ratio of maximum to average stress in the bars $13\frac{1}{2}$ in. long between centers of rivet holes. It also gives the result of the test of stress distribution in a lattice bar of Column No. 1. Table 11 gives the stresses at failure of the various bars tested singly. The average stress on the various

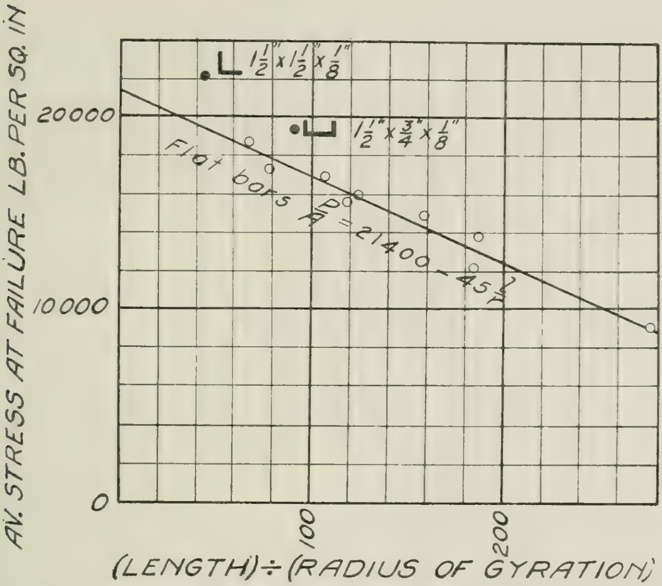

FIG. 26. RESULTS OF COMPRESSION TESTS TO FAILURE OF LATTICE BARS.

TABLE 11.

COMPRESSION TESTS OF LATTICE BARS.

Average of two specimens.

Section of Bar inches	Distance c. to c. of Rivet Holes inches	$\frac{l}{r}$	Stress at Failure lb. per sq. in.	Stress at Failure for Steel of 40 000 lb. per sq. in. Yield Point* lb. per sq. in.
1½ x ¼ flat	20	277	9 900	8 900
1 x ⅜ flat	20	184	12 900	12 200
⅞ x $\frac{7}{16}$ flat	20	158	14 500	15 000
1½ x ¾ x ⅛ channel	20	90	20 800	19 400
1½ x 1½ x ⅛ angle	20	43	22 600	20 100
1½ x ¼ flat	13½	187	15 400	13 800
⅞ x $\frac{7}{16}$ flat	13½	107	16 300	16 800
1 x ⅜ flat	13½	124	16 900	15 900
1½ x ¾ x ⅛ channel	13½	61	bolt sheared	....
1½ x 1½ x ⅛ angle	13½	29	bolt sheared	......
1½ x ¼ flat	8½	118	17 300	15 500
⅞ x $\frac{7}{16}$ flat	8½	67	18 100	18 700
1 x ⅜ flat	8½	78	18 300	17 200
1½ x ¾ x ⅛ channel	8½	38	bolt sheared	......
1½ x 1½ x ⅛ angle	8½	18	bolt sheared	......

* The values in this column were obtained by multiplying the observed stress at failure by $\left(\frac{40\ 000}{\text{yield point determined from tests}}\right)$.

bars, which gave a maximum fiber stress of 40 000 lb. per sq. in., as taken from these tests, has been noted and is given in Table 12. The results of the tests to failure are shown graphically in

TABLE 12.

AVERAGE STRESS IN LATTICE BARS WHICH CORRESPONDS TO A MAXIMUM FIBER STRESS OF 40 000 LB. PER SQ. IN.

Section of Bar inches	Distance c. to c. of Rivet Holes inches	Corresponding Average Stress lb. per sq. in.
⅞ x $\frac{7}{16}$ flat	13½	11 600
1 x ⅜ flat	13½	14 000
1½ x ¼ flat	13½	14 900
1½ x 1½ x ⅛ angle	13½	15 900
1½ x ¾ x ⅛ channel	13½	17 500

TABLE 13.

STRESS IN LATTICE BARS OF COLUMN NO. 1 UNDER CROSS BENDING.

Column tested as a beam centrally loaded over span of 19 ft. 8 in.; lacing bars 1¼ x $\frac{7}{16}$ in.; 17.89 inches c. to c. of rivet holes; rivets ½-in. in diameter.

Bar	Maximum Fiber Stress from Ames Dials	Average Stress from Ewing Extensometer	Ratio Maximum to Average
	"Over" bars in compression		
14 E	6000	2600	2.31
16 E	8300	2000	4.15
18 E	4300	1800	2.39
20 E	7700	1400	5.50
22 E	7000	2900	2.42
24 E	8900	2200	4.04
			Av. 3.47
	"Under" bars		
15 W	4300 c*	2500 c	1.72
25 E	3800 t*	3100 t	1.23
17 E	3900 t	3000 t	1.30
25 W	3900 c	2800 c	1.39
19 W	4500 c	2900 c	1.55
			Av. 1.44
	"Over" bars in tension.		
16 W	7000	3000	2.33
18 W	7000	2200	3.19
20 W	4500	2400	1.87
22 W	5700	2200	2.59
24 W	7000	2700	2.59
26 W	3800	2200	1.73
			Av. 2.38

* c, bar in compression; t, bar in tension.

Fig. 26. The angle and channel bars tested with flattened ends failed in the flattened part at loads no greater than similar bars not flattened at the ends.

Table 13 gives the results of the test for stress distribution in the lattice bars of Column No. 1 as it was stressed in cross bending.

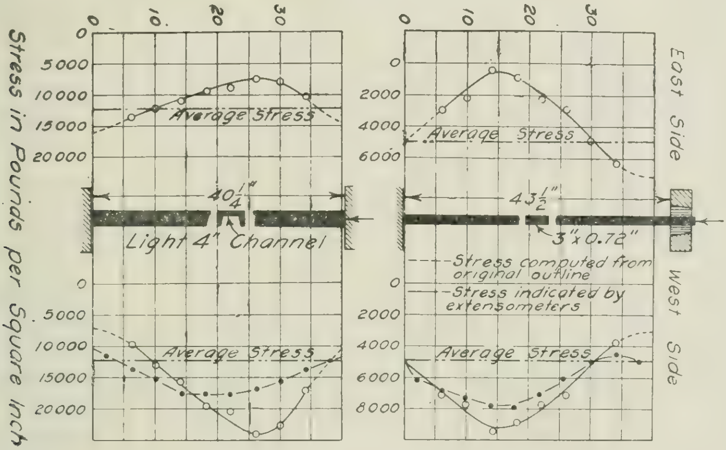

FIG. 27. STRESS DISTRIBUTION IN SMALL COLUMNS.

26. *Tests of Two Small Compression Pieces.*—Tests of two small compression pieces were made in order to study the effect of slight bends and kinks in the column upon the distribution of stress. The deviation from a straight line, in these nominally straight pieces, was measured before the load was applied. The deformations on two opposite faces for a given load were measured. The extensometer was similar to that used on the single lattice bar tests. The instrument was shifted from one position to another along the column. The columns were finally loaded to failure. One of the columns was a flat piece of steel, 3 x 0.72 in. in cross-section, and 46 in. long. It was held at the upper end by wedge grips in the cross-head of the machine and at its lower end rested on a spherical-seated block. The second compression piece was a 4-in. channel 40 in. long. The ends were planed square; the upper end bore on a flat compression plate in the iron head of the machine, and the lower end rested on a spherical-seated block.

TABLE 14.

Tension Tests of Material from Columns.

Test Piece from	Material	Number of Test Pieces	Average Stress at Yield Point, lb. per sq. in.	Average Stress at Ultimate, lb. per sq. in.	Elongation in 2 inches, per cent
Col. No. 1 Angles	Steel	2	43 300	61 600	37
7/16 x 1¼ lacing bar	Steel	2	40 700	58 100	42
1 x ¼ lacing bar	Steel	1	42 400	62 000	38
Channels of wrought-iron columns	Wrought-iron	3	30 700	46 800	17

TABLE 15.

Tension Tests of Lattice Bars.

Shape	Dimensions of Cross-section of Whole Bar inches	Number of Specimens Tested	Average Stress at Yield Point, lb. per sq. in.	Average Stress at Ultimate, lb. per sq. in	Elongation in 2 inches per cent
Channel........	1½ x ¾ x ⅛	1	43 000	57 600	36.5
Angle...........	1½ x 1½ x ⅛	2	45 000	59 300	24.5
Flat............	⅞ x 7/16	2	38 700	57 000	45.5
Flat............	1 x ⅜	2	42 400	61 700	45.8
Flat.......	1½ x ¼	2	44 600	60 800	42.8

Fig. 27 gives the results of tests of the small columns. The dotted line represents the maximum fiber stress computed by considering the eccentricity of loading at any cross-section to be equal to the deviation of that section from a straight line connecting the ends of the column. The deflections were slight, and were neglected in the calculations. The solid line represents the stresses on the two sides of the column, as determined from the extensometer readings.

27. *Tests of Column Material.*—Table 14 gives the results of the tensile tests of samples of materials from various parts of the flange members of the columns, and also of tension tests of lattice bars. Table 15 gives tension tests of lattice bars like those used in the compression tests of lattice bars.

V. DISCUSSION.

28. *The Action of Built-up Compression Pieces.*—In analytical discussions of column action, the stress is usually assumed to vary uniformly from a minimum on one side of the cross-section to a maximum on the opposite side, and the whole cross-section of the column is considered to act as a unit. The longitudinal axis of the column is also considered to take a definite elastic curve under load. In the derivation of most column formulas, it is assumed that the amount of deflection of the elastic curve from the original position of the axis is an important element in fixing the maximum stress in the column. Although these assumptions are generally used as the basis of column formulas, it may be well to consider whether conditions may not exist, in columns of ordinary form and dimensions, which will render doubtful the general applicability of some of these assumptions and will dwarf the effect of others. At any rate, it seems worth while to consider the effect of other conditions in a built-up member. It must be borne in mind that the built-up column is subject to imperfections of fabrication, and that some crookedness and eccentricity must exist. The component parts of the column may be relatively slender and flimsy. Whether there is integrity of cross-section under load, is a question. In the tests herein described, the amount of deflection from the original axis, for loads up to a point somewhat below incipient failure, was found to be slight (generally between 0.04 and 0.1 in.), much smaller than necessary to account for the stresses observed in the columns.

The action of short columns at failure may be expected to be different from that of longer columns, although the stresses up to incipient failure may be the same. Granting that the conditions of non-straightness are such that the distribution of stress over the cross-section is the same for the two lengths of columns, and that the deflection of the column is so slight as not to affect materially the stresses developed, the longer column will be in more danger of immediate and sudden collapse after the yield point of the material in any fiber has been reached, and the total load carried before complete failure will, in general, be less. This is because, in a ductile material, after the stress at one side of the column has passed the yield point, the total resistance of the section to compression will increase, while the resistance to cross bending may not. Under the conditions named, the bending moment due to eccentricity will be the same until the yield point in some fiber is reached. After yielding begins, the greater deflection in the longer column rapidly increases its relative eccentricity, and more rapid failure may be expected than with the shorter column.

29. *Indications of Data.*—It will aid in the interpretation of the data of the distribution of stress over the channel members of the columns to point out a few simple indications. Reference may be made to the diagrams in Fig. 8 to 15, and Tables 2, 3, 8, and 9.

1. Any lack of agreement between the average load stress and the average of the stress given for the four centers of gravity of channel flanges may be ascribed to errors of observation.

2. If the stress at the center of gravity of one channel is above the average stress throughout the length of the column, and the corresponding stress for the other channel is similarly below the average stress, there must be an eccentricity in the application of the load at the two ends. If the stresses at the center of gravity of one channel member form in the diagram a straight line which crosses the line of average stress, and that for the other channel crosses in the opposite way, the eccentricity of the load application must be oblique.

3. If the stress at the center of gravity of a channel in near-by points is greater first in one channel and then in the other, the change may be due to crookedness of the column throughout that part of the length.

4. If, in one channel or in one channel flange, the stress at the center of gravity remains constant and that of the extreme fiber varies, the change may be due to local crookedness of this channel and there will be a lateral bending of this member.

5. If the front side of a channel has a higher stress than the back side, there must be bending action through its web, and *vice versa.*

6. Changing stresses in the diagonally opposite corners of a channel may indicate twisting of the channel, and another combination of stresses may indicate a twisting or oblique distortion of the column as a whole.

An inspection of the diagrams shows that all these indications are found in the tests.

7. To be in accord with the principles of column formulas of the Rankine type, there should be from end of column to middle a regular increase in the stress in one channel or in one flange of a channel and a corresponding decrease in the stress in the other. Verification by an agreement between the distribution of stress and the theory would be important. It will be seen that this verification was not obtained.

30. *Does the Built-up Column Act as a Unit?*—Engineers have often expressed doubt as to whether the parts of a built-up column act as a unit, although column formulas assume this unity of action. The tests throw some light on the question of the integrity of cross-section under load. The individual channel, of course, acts as a unit to resist bending action, though there are indications of twisting. The integrity of the whole section with reference to a plane parallel to the lacing seems probable, except as twisting action exists. With reference to a plane through the axis perpendicular to the plane of the lacing, this unity of action is not so certain. The tests on the distribution of compressive stress and likewise the cross-bending tests of the columns indicate that these built-up columns did not in all cases act as a unit but rather as two members not fully restrained by the lacing. The stresses in two channels as points in the same cross-section do not give the regularity of variation which would exist if the column bent as a unit. The elastic curve assumed by Column No. 1 under cross-bending load, shown in Fig. 18, differs from the computed elastic curve, though that for the wrought-iron column gives little difference. In the case of the posts of the White Heath bridge, however, there is much closer agreement and a seemingly closer approach to unity of action.

31. *Effect of Non-straightness of Built-up Columns Upon Distribution of Compressive Stress.*—The effect of crookedness or other irregularities of a constituent member of a built-up column may be realized if a rough analysis of the case be made. Consider a part of one of the channels forming a column, taking the length between the connections of two adjacent lattice bars. This member is under compression. Owing to non-straightness or to the non-homogeneity of the material, the load on this short piece is not evenly distributed over the section; that is, it is not centrally loaded, but may be considered to have an eccentricity with respect

to the gravity axis. Call this eccentricity e (Fig. 28). Neglect any deflection of the piece under consideration due to the load. Call the compression load coming on this piece P; A its area of cross-section; I its moment of inertia about YY, and r the corresponding radius of gyration; and c the distance from YY to the remotest fiber. Then the bending moment due to the eccentricity is Pe. The maximum stress will be

$$f = \frac{P}{A} + Pe\frac{c}{I} = \frac{P}{A}\left(1 + \frac{ec}{r^2}\right).$$

The excess of the stress in the extreme fiber of the piece over the average stress, produced by the eccentricity e is then $\frac{P}{A}\frac{ec}{r^2}$, and hence the term, $\frac{ec}{r^2}$, gives the proportionate excess of stress in the extreme fiber. This value is applicable to the channel, or to one flange of the channel, or it may be applied to the column as a whole by using the properties of the whole section. In the single channel under consideration, c is relatively large and r is relatively small, and the excess of maximum stress for a given eccentricity e may be expected to be relatively large. It will be seen that for an excess of 50% in the extreme fiber of a channel of Column No. 1, e, by this formula, would be 0.045 in., and, in the wrought-iron columns, 0.057 in. A slight variation from straightness in a channel will account for considerable increase of stress.

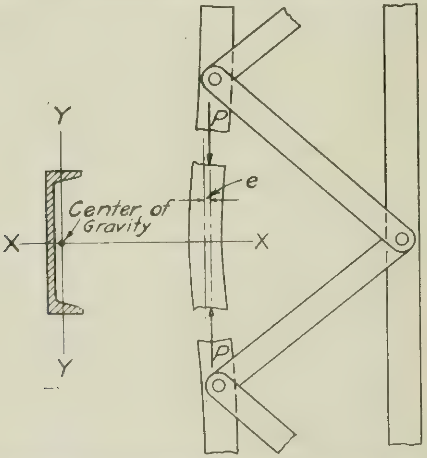

Fig. 28. Effect of Eccentricity in Channel Members.

32. *Excess of Maximum Fiber Stress over Average Stress in Channel Members.*—The diagrams and data show that the compressive stress is unevenly distributed over the cross-section of the columns tested, and also that there is great variation in this distribution at various sections along the length of the column. It will be noted that in a number of sections the excess of stress was from 40 to 50 per cent. In one test of Column No. 1, an excess of 67 per cent was found, and in the White Heath bridge an excess of 73 per cent. Possibly these values were unusual or the observations were erratic, but the indications of a fiber stress of from 40 to 50 per cent in excess of the average stress were not uncommon.

It may be seen that among the causes to which the high fiber stress may be attributed are (a) non-straightness of the column as a whole, (b) non-straightness of the component channels, or eccentricity in the delivery of stress to them by the lacing, and (c) unknown eccentricity in the application of the load. It would be of interest to know how much of the increase of stress may be due to any one of these conditions. A study of the tests of Column No. 1 shows that generally only a small amount may be said to be due to non-straightness of the column as a whole. In but few cases is it found to be more than, say, 5 per cent; in four places it seems that the excess attributable to this may be estimated to be between 20 and 25 per cent. The effect of non-straightness of the individual channels seems to be greater. At several points the excess of stress attributable to this cause appears to be from 30 to 50 per cent. As already noted, a kink in the channels of 0.045 in. would give, by the analysis made, an eccentricity sufficient for a 50% increase in stress. Not all of this crookedness need be between adjacent rivet points, as the stress may not become normal for some distance on either side. The effect of the third condition, eccentricity of application of the load, will vary with the construction. In Column No. 1 the effect of undetermined eccentricity of application of load appears to be not nearly as great as the effect of non-straightness of the component channels.

In the wrought-iron columns, which are much stockier, the lack of straightness in individual channels has less effect, seemingly less than 15 per cent, and much the larger part of the high fiber stresses appears to be due to general column eccentricity or to eccentricity of loading.

The results for the posts of the White Heath bridge are of interest in this respect. It is evident that the effect of non-straightness of channels was not large, and also that the effect of non-straightness in the column as a whole was relatively small. There is, however, an evident bending in the direction of the web of the channels. For example, in U_3L_3 South, the back side of the channels has the maximum stress at the top and the front side at the bottom. The bending moment producing this may be due to obliquity of end pressures or to a bending by the connecting floor-beam and top cord. A twisting action is also apparent. Posts U_3L_3 North gave quite similar results.

33. *Effect of Cover-plates and End Connections.*—In the tests of the White Heath bridge, the effect of the cover-plate seems striking. The upper chord, U_3U_4, composed of two built-up channels with one cover-plate, gave an excess fiber stress of 20 per cent at the worst section, while the post, composed of two channels laced on both sides, gave a maximum of 73 per cent. The high value in the posts may be due to other causes, but it seems reasonable to expect that the cover-plate will act to reduce the irregularities in fabrication. Engineers have stated that columns having a cover plate are fitted into their places during erection with less labor than is required for columns with lacing on both sides. Tests on the stress distribution of such columns would be valuable as affording a basis of definite comparison.

The connections of the ends of posts evidently exerted a very noticeable effect on the stress distribution. In one of the posts tested, the stress was greatest at one corner of the post at the top and at the diagonally opposite corner at the bottom. It will be remembered that the posts were riveted to the top chord, and were connected with the lower chords by pins. The floor-beams were riveted to the sides of the posts, and this connection affects the stress distribution. Readings of deformations taken on the floor-beams and posts show that the loaded beam was partly restrained at the ends by the post, though this restraint introduced a bending moment at the end of the post only about one-quarter as great as at the center, and that there was an appreciable bending in the post.

34. *Stresses in Column Lacing.*—If the load carried by one channel of a column was the same throughout its length, no stress would be carried by the lattice bars. Such stress is developed

whenever there is a change in the relative amount of loads carried by the two channels. If, at the section AB (Fig. 2, p. 11), there is an equal division of load between the two channels, and also at the section CD, and if at some section EF, the division of load is unequal, it is evident that the lattice bars must be called into action to transmit this stress, and that transverse shear exists in the interval. In general, the conditions producing this will be complex, rendering analysis unsatisfactory, except in so far as the shear may be due to a known eccentricity of loading.

It is evident from the tests that the relative stress in the two channel members varies considerably from end to end and that the stress in the lattice bars also varies. It seems probable that the transverse shear developed may be traced largely to irregularities in outline, or at least that these irregularities may be expected to cover up other causes of stress in the lacing of centrally-loaded columns, if we include in such irregularities all unknown eccentricity. The futility of attempting to determine analytically the stresses in column lacing, using as a basis either a bending moment curve which varies regularly from end to middle or an assumed deflection curve, is apparent from a study of the variation of stress in the columns of the tests and in that of the lattice bars.

The amount of transverse shear necessary to produce the maximum observed lattice-bar stress (given in Table 6) is of interest, though of course it cannot be taken to be conclusive. The measurements were generally made at working loads. So far as observations were made on columns tested to failure, the distribution of stress remained much the same up to incipient failure. The values given in Table 6 indicate maximum average stresses in the bars such as would be caused by a transverse load ranging from 2% to 6% of the central compression load or of a transverse shear of 1% to 3% of the load.

35. *Compressive Strength of Lattice Bars* —In the discussion of stress developed in column lacing, the stress considered was the average over the bar. As usually attached, there is considerable flexure in the bar, and the ability of the bar to carry this eccentric load should be considered. The bars are most likely to fail in compression, since they act as long columns eccentrically loaded. This compressive strength may be greatly diminished by the bending which they frequently receive in transportation and erection.

The tests of individual lattice bars (Fig. 25 and Table 12) show that the maximum fiber stress may be several times the average stress. It is also seen that even in a short lacing bar the maximum load carried is only about one-half the yield point of the material. The necessity of using very low working loads on lattice bars appears to be important. It will be noted that at low stresses there is similarity of distribution of stress in the slender bars and in the thicker bars, but the slender bars fail at smaller computed fiber stress.

The results of tests to destruction of individual lattice bars (flats) are fairly well represented by the formula:

$$\frac{P}{A} = 21\,400 - 45\frac{l}{r}$$

where $P =$ load at failure in pounds, $A =$ area of cross-section in square inches, l is the distance in inches from center to center of rivet holes, and r is the radius of gyration, in inches, of the cross-section of the lattice bar. The results of the tests were adjusted so that this formula applies to material having a yield point of 40 000 lb. per sq. in. These results may be considered to be applicable to "under" lattice bars. For "over" bars it seems probable that the average stress at failure would be considerably less. If $\frac{l}{r}$ is 0 in the above formula, that is, if we have a very short lattice bar, the average stress over the bar at failure would be 21 400 lb. per sq. in. If the extreme fiber stress in this short bar is 40 000 lb. per sq. in., the yield point of the material, the equivalent eccentricity of loading (e) which would produce this, may be found from the equation

$$40\,000 = 21\,000\,(1 + \frac{e \times \frac{1}{2}t}{r^2}),$$

where t is the thickness of the bar. The resulting e is found to be very nearly $\frac{t}{7}$. We may then regard the lattice bar to have been loaded with an initial eccentricity equivalent to $\frac{1}{7}$ the thickness of the bars.

36. *Effect of Form of Section.*—The large variation in stress over a cross-section of the column and the marked changes in stress from section to section along the column are evidently due to local crookedness, local eccentricity, lack of rigidity of lacing,

and other variations which may be independent of the general flexural curve usually assumed in deriving the usual formulas for column strength. It would seem that the form of section (including in this term the relation of the thickness of the metal to the section as a whole) has a bearing on the strength. The thinner and flimsier component angles and channels are more liable to receive kinks, bends, and distortions before and during punching and riveting in the shop and in the later transportation and erection than are the stockier sections. The value $\frac{ec}{r^2}$ of the formula given on page 54 may be expected to vary with the form of section used. Besides, some sections are better fitted to withstand lateral twisting or diagonal distortions and to preserve the integrity of the cross-section than others. The wrinkling tendency in plates and thin parts under compression, heretofore referred to, is another element affecting the strength of columns. It may be expected, then, that differences in section, in type of component parts, in method of relating and tying the parts together, and for the same type of section differences in relation of thickness of parts to extreme dimensions of sections, will have an important influence upon the compressive strength of columns. It follows, therefore, to give the best results, that the section of the column, and its web construction, should be chosen so that (1) the shop processes shall leave the component parts of the column in the best condition (giving the minimum of bending, buckling, twisting, and interior eccentricity), and (2) the section will be adapted to resist local lateral bending and twisting action. Evidently, different forms of section may be expected to give considerable difference in strength. This difference has been recognized heretofore in formulas which have been proposed and used for certain types of columns.

37. *Effect of* $\frac{l}{r}$.—A study of the tests does not show any relation between the stresses actually observed and the stresses computed by column formulas. The high stresses do not come where the curve of flexure used as the basis of formulas of the Rankine type would place them, and the position and amount of the maximum stresses are very irregular. Although there is little range in the slenderness ratio ($\frac{l}{r}$) of the columns tested, no

effect is noticeable for which the value of $\frac{l}{r}$ would seem to have much influence. This view seems to be in disagreement with theoretical considerations. The lengths for which Euler's formula may be expected to govern column strength are much greater than the length tested, and probably are higher than is generally assumed in engineering literature. Within the critical length at which Euler's formula governs, the general flexure of the column as a whole under load has less influence upon the strength of the column than is ordinarily assigned to it, and therefore the influence of $\frac{l}{r}$ is not as great as is represented in the usual column formula. Of course, the longer the column the more the amount and influence of its defects may be. The recent tests of columns at the Watertown Arsenal indicate that, within the range of lengths tested ($\frac{l}{r}$, 25 to 175), the reduction in strength at elastic limit with increased length is relatively small, perhaps not much more than may be due to increased variation from straightness and homogeneity. In this connection it should be noted that the column formulas in common use give altogether too high strengths for short columns, if the elastic limit is to govern. So far as ultimate strength is concerned, tests show the strength of short columns to be considerably above their elastic limit, but beyond a limit of, say, 35 for $\frac{l}{r}$, there is much less difference between elastic limit strength and ultimate strength.

38. *Column Formulas.*—That the column formulas in common use have limitations, has been well understood, but the effect which the conditions of the component parts of a compression member exert on the distribution of stress over the section has not been appreciated, nor has that of eccentricity of connection of latticing, and of the possible non-integrity of section. It would seem quite probable that, for columns of the same length and containing the same amount of metal, one which is of stocky form and in which the metal is distributed so as to resist local flexural and torsional action will be much stronger and more satisfactory than a column of more flimsy form, which has its metal spread in thinner sections, even though the slenderness ratio, $\frac{l}{r}$, of the for-

mer may be considerably more than that of the latter. It seems reasonable to expect that a form of section which resists lateral bending, torsional and collapsing stresses, will be much more satisfactory than a more flimsy type of column, for the lengths most common in ordinary bridge construction. If these statements are trustworthy they express an important principle. For the longer lengths, the slenderness ratio must exert a stronger influence. For the strength of the component angle, channel, or other structural shape used in a built-up compression piece, many engineers have been satisfied with the provision that the slenderness ratio of the component member shall be less for the length between the points of attachment of lacing than the slenderness ratio for the column as a whole, and have given little attention to the possible non-integrity of the section or to the probable effect of imperfections of manufacture. Fortunately, the large influence of the slenderness ratio in column formulas has given sections with which failures have not occurred. Whether a column formula should include a factor depending on the form of the section and the relative thickness of the metal, or whether the allowable stresses for any form of column should be based on experimental data for the section used, will depend on future developments.

39. *Field for Investigation.*—The tests herein recorded have shown the practicability and also the importance of making tests on the distribution of stress over built-up columns within the elastic limit, both under laboratory conditions and in field service. It is evident that much experimental information is needed on the stresses which are developed in compression members built under ordinary conditions of fabrication and erection before a satisfactory column formula may be established. Tests giving the needed information involve extreme care, and they are expensive, with regard to time and labor, whether done in the field or in the laboratory. A full study of the action of the compressive piece under loads which do not stress the material beyond the elastic limit should be included. The expenditure involved is far beyond that of tests to destruction alone. An investigation should be accompanied by a careful study and analysis of the tests and results. A program of tests need not involve a large number of test pieces; but, to be really useful for the purpose in view, the time devoted to the test and the study of each piece must be ample, and the total

cost of even a fairly comprehensive investigation will be large. It may be expected, however, that the value of the results would repay many times the cost of the work, and the expense would be justified by the added security and, perhaps, by the economy of metal which might result from the investigation.

40. *Summary.*—The main points brought out in the preceding discussion may be recapitulated as follows:

1. The practicability of making tests to determine the actual stresses which are developed under working loads and up to the elastic limit of the material in the members of a column, throughout its length and over its cross-section, has been shown. The results significantly point to the importance of making investigations of this kind. The experimental work involved is tedious and laborious, and of course, the work requires skilled and experienced experimenters. The need of such information has been recognized heretofore, but tests have not been taken up because of the supposed impracticability.

2. An important result of the tests is the evidence that considerable local flexural action exists in the channel members of the columns, such as may be produced by lack of straightness or by any method of applying the load eccentrically. This is especially true in the flimsier column.

3. The condition of flexure varies markedly throughout the length of the channel member, in some cases the maximum compression in one cross-section being at the extreme fiber on one side of the channel, and in a near-by section the other side of the channel showing the excess of stress.

4. There were also indications of sudden changes in the relative amount of stress carried by the two channels at near-by sections, indicating general flexure of the column.

5. The measurements made indicate in a number of cases stresses in the extreme fiber from 40% to 50% in excess of the average stress, and in some cases even higher.

6. The amount of eccentricity necessary to account for the increase of stress found in individual channels, based on lack of straightness and the ordinary theory of flexure, is relatively small.

7. The amount of deformation observed in lattice bars is relatively small, and its variation throughout the length of the column is quite irregular. The measurements indicate a stress in

the lattice bars which would be produced by a transverse shear equal in amount to 1% to 3% of the applied compression load, or to that produced by a concentrated transverse load at the middle of the column length equal to 2% to 6% of the compression load. The stress referred to is the average stress over the section of the lattice bar.

8. It seems futile to attempt to determine the stresses which may be expected in column lacing for central loading by analysis based on theoretical considerations or on data now available.

9. When the column was tested as a beam, the extreme fiber stress in lattice bars in compression was found to be from 1.4 to 5.5 times the average stress over the cross-section of the lattice bars, and the extreme fiber stress in lattice bars in tension was found to be 1.7 to 3.2 times the average stress.

10. Tests of individual lattice bars for load-carrying capacity under conditions which resemble those of service show that the usual form of bar is a very inefficient compression member when loaded eccentrically through a riveted connection. The ultimate strength was in no case as much as one-half of the yield point of the material.

11. The formula, $\frac{P}{A} = 21\,400 - 45\frac{l}{r}$, represents fairly well the ultimate strength of the flat lattice bars tested, based on material having a yield point of 40 000 lb. per sq. in.

12. It seems evident that the component members of a built-up column do not act together in such a way as to give entire integrity of cross-section in resisting bending.

13. The distribution of stress under working loads, and even up to incipient failure, may be different from that which exists after the column becomes crippled. This is due to the yielding of the more strained parts after the yield point is reached at any fiber, and a consequent redistribution of stress.

14. The sudden failure of a test column at a relatively low load by buckling of the lattice bars is accounted for when the amount of transverse shear developed in other test columns and the strength of lacing found in lattice-bar tests are taken into consideration.

15. No relation has been found between the stresses actually observed and the stresses computed by column formulas. The stresses do not increase toward the middle of the length of the

column, as may be expected from the Rankine form of analysis, but are quite irregular in their location and distribution.

16. Much of the excess of extreme fiber stress over average stress is evidently attributable to local crookedness of piece, eccentricity of bearing of lattice bar connection, lack of rigidity of lacing, and other irregularities that are due to the condition of the material and its fabrication, and what may be considered to be inherent variations and defects in the constructed compression piece. Within the elastic limit of the material and for the lengths most commonly used the lateral flexure of the column as a whole is very slight, and slenderness ratio can not be said to be the governing consideration. Undoubtedly, the chances for variations from the ideal column will become greater as the column length becomes greater, and these variations may have a more marked effect upon its strength.

17. It is evident that the form of section is important. Stocky and stiff component members are less liable to receive kinks, bends, and distortions during and after fabrication and will resist the effect of such imperfections with less resulting stress than will flimsy pieces. Some column sections are well calculated to resist bending, buckling, and twisting, and are so tied together as to preserve integrity of section, while others have less resistance to general distortion. Even the wrinkling action in plates and thin parts needs consideration. It seems reasonable that, for columns of the same length and containing the same amount of metal (within the ordinary dimensions), one which is of stocky form and in which the metal is distributed so as to resist local flexural and torsional action will be stronger and more satisfactory than a column of more flimsy form, which has its metal spread in thinner sections, even though the slenderness ratio, $\frac{l}{r}$, of the former may be considerably more than that of the latter. Further, a section which will come through the shop and erection processes with the least imperfections has advantages.

18. This field of investigation is a promising one, and its importance to the engineering profession warrants its being taken up in a thorough and comprehensive manner. Full information on many matters is needed before better and more nearly satisfactory column formulas may be established.

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THE STRENGTH OF OXYACETYLENE WELDS IN STEEL

BY HERBERT L. WHITTEMORE, ASSOCIATE IN THEORETICAL AND APPLIED MECHANICS*

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*Since the manuscript for this bulletin was submitted, Mr. Whittemore has accepted appointment as Engineer of Tests of the U. S. Ordnance Department at Watertown Arsenal.

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THE STRENGTH OF OXYACETYLENE WELDS IN STEEL.

I. INTRODUCTION.

1. *Preliminary.*—Among the recent developments which give promise of wide-spread use in the field of metal working, is that of the oxyacetylene blowpipe. Due to the high temperature of the flame produced by this instrument, results are obtained which heretofore have been impossible. The most important use of the oxyacetylene flame is the welding of two pieces of metal by fusion without the necessity of adding either flux or soldering or brazing material. This process is known as autogenous welding.

This process has already become important commercially. It seems probable that when its effectiveness and availability have become known, it will be quite generally used, both by large and small metal working shops. In this connection the following facts may be noted:

(1) The combination of oxygen with acetylene produces one of the highest temperatures known,—the highest due to combustion and about equal to that obtained in the electric furnace.

(2) Methods of producing calcium carbide in the electric furnace, and methods, recently perfected, of producing oxygen by the distillation of liquid air, and by other means, have reduced the cost of these gases to the point where they are commercially available.

(3) The oxyacetylene blowpipe, formerly liable to dangerous explosions, has been perfected until entire safety is claimed.

(4) The necessary apparatus, when conditions demand extreme simplicity, consists only of a small tank of compressed oxygen and another of acetylene dissolved in acetone, both connected to the blowpipe by rubber hose. It is easily portable and can be used in almost any place or position.

(5) Skill in operating the blowpipe is readily acquired by an ordinary workman.

The general applicability of this process to welding depends upon two things: first, the strength and other physical properties of the welds; and second, the cost of the work. Of these, the first is the more important. An extensive search for data upon the matter of strength showed that very little had been published, merely a few general statements and still fewer definite ones. Most of the latter, however, appeared to be of doubtful accuracy. References to articles on this subject are given in the bibliography.

The process has been used successfully for the following work:

(1) Welding tanks and sheet metal work of all descriptions.

(2) Welding frame joints for automobiles, making a rigid structure all in one piece.

(3) Adding metal where needed, usually in small quantities; for example, eliminating defects in castings, particularly in steel castings, such as blowholes, etc., or adding metal to a piece which has been machined under size.

(4) Repairing boilers by either welding cracks, patches, etc., or adding metal where "grooving" or "pitting" has occurred.

(5) Bonding of electric traction rails by fusing the copper bond to the rails.

(6) Repairs of all kinds, made necessary by breakage. For example, a cast-iron punch press frame, broken at the throat, has been welded so that practically it is as useful as ever.

While the oxyacetylene blowpipe method of welding may be applied successfully to a very wide range of work in emergencies, such as "break-down repairs", etc., the cost of the necessary gases for welding thick pieces is so high that this method will never entirely displace coke, gas, or electric welding outfits for manufacturing conditions. Its field is especially *repair work*, *field work*, and manufacturing operations on *pieces of small cross-sectional area*, say, plates not exceeding ¼ in. in thickness.

2. *Scope of Tests.*—The experiments recorded in this bulletin were undertaken with the aim of adding to the information regarding the strength and other physical properties of oxyacetylene welds in steel, inasmuch as steel is the most important metal used in commercial construction. The number of tests was made large enough, it is hoped, to make the results representative of the results which may be obtained under favorable commercial conditions. Although circumstances limited the work to a small range in the thickness of the steel plates, an attempt was made to determine the effect of other variables, such as thoroughness of fusion, forging and heat treatment, and flame regulation, which might have an effect on the welds.

Little attention was paid to the matter of cost of welding the test pieces, as data of cost are of doubtful value unless obtained under commercial conditions. Several of the references listed under VI. Bibliography discuss this matter quite fully, and the firms supplying oxyacetylene welding apparatus are willing to undertake work for prospective customers and thus determine experimentally the time and materials required. In any case, there should be no excuse for operating a blowpipe for any length of time under commercial conditions without estimating the cost, but to obtain data on the strength of the welds requires apparatus and time not usually available, so that there is likely to be much doubt on the latter subject even where the process has been in use for long periods of time.

Incidentally, an investigation was made of the effect of flame regulation upon the strength of the weld and upon the proportions of oxygen and acetylene in the blowpipe flame. The record of experience in blowpipe manipulation and skill in welding as the work progressed, together with other information obtained, will, it is thought, be of service to users of the oxyacetylene blowpipe.

3. *Acknowledgment.*—The apparatus used was a part of the equipment of the Laboratory of Applied Mechanics of the University of Illinois, and the work was carried on in the Laboratory as an investigation for the Engineering Experiment Station. All the work of welding and testing was done by the writer.

In making the chemical analyses of the gas samples, valuable assistance was rendered by R. H. Jesse, Jr., Ph. D., of the Chemistry Department, University of Illinois, to whom much of the credit for this part of the work is due.

4. *Historical.*—The oxyacetylene blowpipe is an outgrowth of the blowpipes in common use which are supplied with coal gas and air. Attempts to increase the temperature of the flame led to the use of combustible gases having higher thermal values per unit of volume, and to the use of pure oxygen. In this way, a given number of heat units, produced by the combustion, were confined to the smallest possible volume of gas. The use of pure oxygen eliminated the nitrogen present in the air which served only to dilute the gases and to lower their temperature in a corresponding degree. The result of these changes was to bring

into use the oxyhydric blowpipe, which is extensively used in Germany for the autogenous welding of steel and for other work.

Acetylene, as a substitute for hydrogen, offered theoretic advantages, as its thermal value is 1846 British thermal units per cubic foot. This amount is over six times the thermal value of hydrogen, which is 293.5 British thermal units. Attempts to use acetylene, however, resulted in serious explosions. The first successful oxyacetylene blowpipe was devised by E. Fouché, a French investigator, who experimentally determined the rate of propagation of an explosion in tubes of varying cross-section, when they were filled with an explosive mixture containing acetylene. He then perfected a blowpipe in which the acetylene is supplied through small tubes at a rate greater than that of the propagation of the explosion back toward the acetylene reservoir. While this precaution would, apparently, be unnecessary if the tubes contained only pure acetylene, there is always some danger that, on account of imperfect operation, the oxygen which is under higher pressure than the acetylene will be forced into the acetylene passages or even into the reservoir itself.

In order that use may be made of the acetylene gas under the pressure at which it is usually generated (about 20 in. of water or less) the Fouché blowpipe uses the oxygen under pressure to draw the acetylene into the blowpipe on the injector principle. This avoids the necessity for an expensive compressor for the latter gas.

Fouché invented his blowpipe probably about 1902 or 1903, but the process was not introduced into this country until 1904, when the Fore River Shipbuilding Co., of Quincy, Mass., installed oxyacetylene blowpipes for welding light sheets of metal which had formerly been riveted.

Several blowpipes have since been designed to use both gases under pressure, and they are said to have the following advantage over the Fouché blowpipe. Both gases, being under pressure, maintain quite accurately their relative proportions when once properly adjusted. In the injector blowpipes, on the contrary, changes in temperature of the blowpipe and the copper tip forming the outlet cause some variation in the size of this opening and consequently variations in the relative proportions of the gases.

II. Welding Apparatus and Methods.

5. *Apparatus.*—The Fouché blowpipe was selected for these experiments because it is probably the best known and most widely used. While there may be differences among various oxyacetylene blowpipes in regard to convenience of operation, there can be very little difference in the efficiency of joints welded by these various blowpipes.

A welding equipment was secured from the American firm controlling the Fouché patents. It consisted of a Fouché blowpipe, a hydraulic back-pressure valve, a tank of compressed oxygen, an oxygen pressure regulator, a pair of blue glasses and a rubber hose.

In order to avoid the trouble and expense of an acetylene generator for this work, tanked acetylene was secured from The Commercial Acetylene Company, 80 Broadway, New York, from their plant at Joliet, Illinois. For commercial work of any magnitude, acetylene would usually be generated, as the cost would then be about one-third that of tanked gas. Tanked acetylene offered advantages for experimental work, among which were the probability of a more uniform quality of gas than would have been obtained from a generator, and also the possibility that the gas was more nearly pure. This company furnished a tank of acetylene, a high pressure gauge, and an acetylene pressure regulator.

6. *The General Arrangement of Apparatus as Used.*—The apparatus was arranged as shown in Fig. 1, the parts being as follows: A, work bench, covered with fire brick; B, blowpipe; C, oxygen pressure regulator; D, oxygen tank; E, hydraulic back pressure valve; F, acetylene pressure regulator; G, water U–tube for pressure of acetylene as supplied to blowpipe; H, gauge for acetylene tank pressure; I, acetylene tank.

The arrangement of the oxygen connections and of the acetylene connections is shown in Fig. 1. The acetylene supply is connected to the back pressure valve E. The hose J–K conveys the gas from the back pressure valve to the blowpipe. The oxygen tank is shown with its pressure regulator, C, the gas passing to the blowpipe through the hose L–M.

7. *Oxygen Supply.*—The oxygen tank had a capacity of 100 cu. ft., when charged to 120 lb. per sq. in., and weighed, empty,

132 lb. The oxygen was about 95% pure, nitrogen being the principal impurity.

In order to maintain a constant pressure suitable for use in the blowpipe, a regulator was attached to the oxygen tank. This is shown in Fig. 1. The pressure gauge, N, measures the tank pressure and allows computations to be made, at any time, of the amount of oxygen remaining in the cylinder. The thumb screw P adjusts the pressure of the gas as delivered to the blowpipe, which is measured by the pressure gauge O.

8. *Acetylene Supply.*—The acetylene tank had a capacity of 225 cu. ft., when charged to 150 lb. per sq. in. pressure. The tank was 12 in. in diameter by 36 in. long and weighed 120 lb. These tanks are packed with asbestos disks before the ends are closed. The asbestos is then saturated with acetone (a species of wood alcohol,) which at 10 atmospheres, or 150 lb. per sq. in. pressure, absorbs ten times its own volume of the gas at a normal temperature, thus increasing the storage capacity of the tank tenfold. Absolute safety for this method of storage is claimed by the manufacturers from whose catalog the above information regarding the tank was obtained. Analyses made by the firm supplying the acetylene indicate that the gas used was about 99.6% pure.

The acetylene tank I with its valve Q is connected by a pipe to the constant pressure regulator F. The pressure gauge H measures the pressure in the acetylene tank; with the pressure known, the amount of gas contained at any time may be computed.

This regulator was not provided with means for adjustment, but a pressure in the outlet pipe of about 12 in. of water was maintained. A U-tube filled with water and connected into this outlet pipe, (G, Fig. 1), allowed this pressure to be measured. It varied somewhat, depending partly upon the amount of water in the back pressure valve.

9. *Hydraulic Back Pressure Valve.*—A section through this valve is shown in Fig. 2. Water is supplied through D and G, and brought to the proper level, E, by opening the cock F, and draining any excess, after which F is closed. The acetylene enters through the cock B and bubbles up through the water, then passes to the blowpipe through cock C. If, for any reason whatever, the direction of flow is reversed, the water level at E

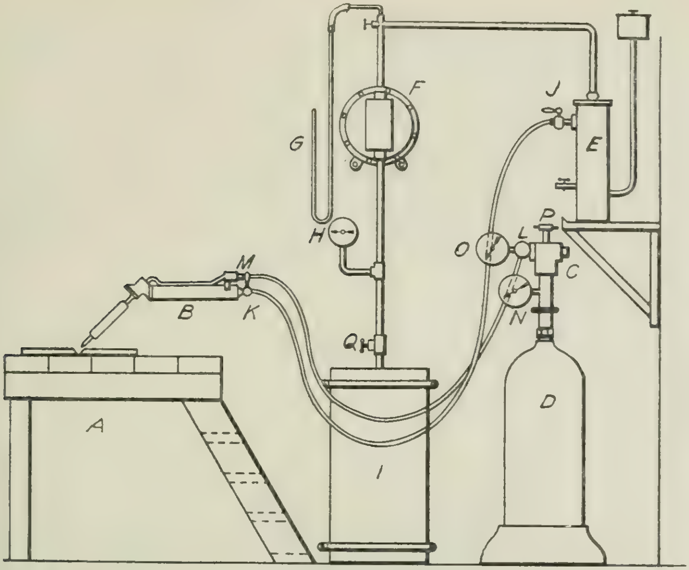


FIG. 1. GENERAL ARRANGEMENT OF OXYACETYLENE WELDING APPARATUS.

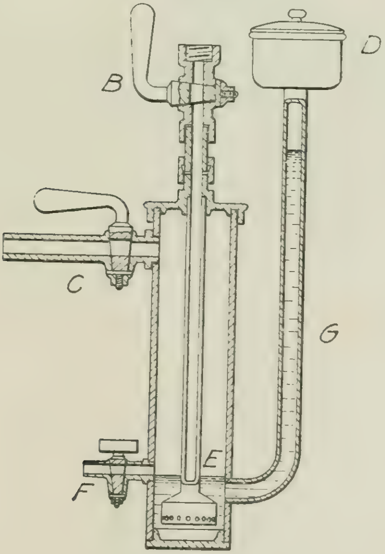


FIG. 2. BACK PRESSURE VALVE FOR ACETYLENE.

falls, the water in G rising until a free passage is provided through G and D to the outer air. This makes it impossible for oxygen to pass into the acetylene passages further than the back pressure valve.

10. *Blowpipe.*—The Fouché blowpipe is shown in Fig. 3. The oxygen enters at A and the acetylene at B. The amount of acetylene is regulated by cock C, which, therefore, controls the relative proportions of the two gases. The sizes, with their capacities and gas consumption, are given in Table 1.

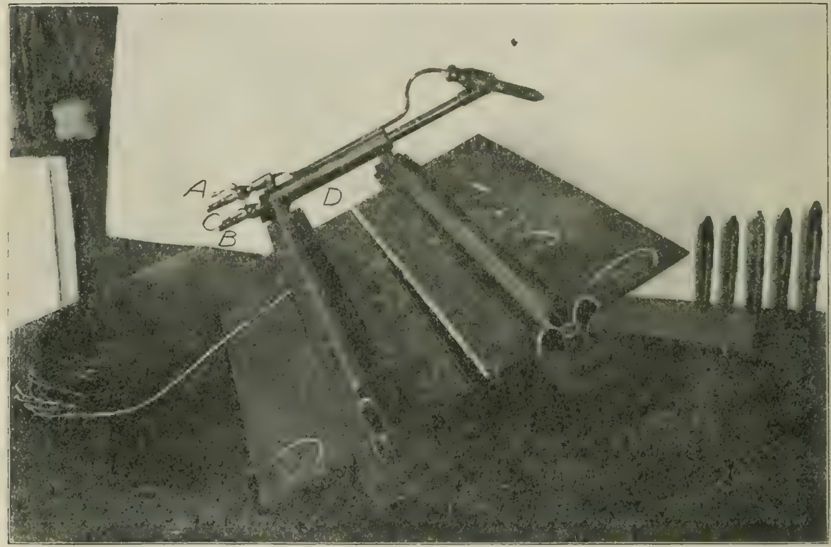
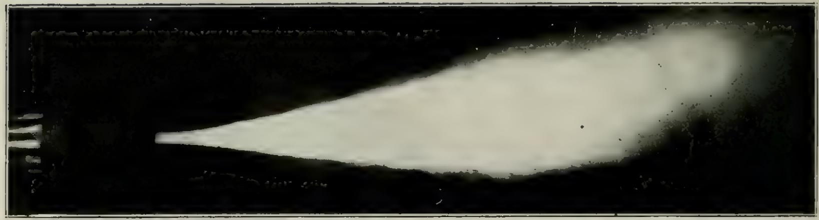


FIG. 3. FOUCHE BLOWPIPE WITH REMOVABLE TIPS AND TEST STRIP READY FOR WELDING—SECOND METHOD.

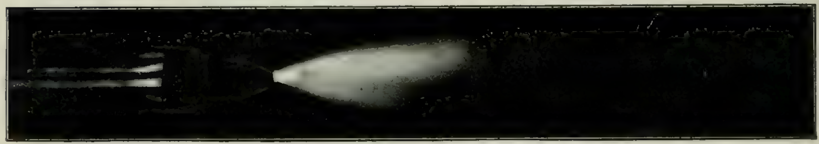
Each of the above sizes is intended for use only on plates of the thickness stated. The use of an unsuitable size of blowpipe will result in loss in economy.

11. *General Methods of Welding.*—There are two methods of making autogenous welds. The first, suitable for thin plates, requires that the edges be brought into perfect contact. They are then fused together without the addition of any material. The second, used for thick plates, consists in fusing into a groove formed by the beveled plate edges, material similar to that in the plate. The thickness generally given as the dividing line between



(a) ACETYLENE FLAME IN AIR.

(b) EXCESS-ACETYLENE FLAME (DOUBLE CONE).



(c) NORMAL OR CORRECT OXYACETYLENE FLAME.

(d) EXCESS-OXYGEN FLAME (SHORT CONE).

FIG. 4. VARIATIONS IN THE FLAME OF THE BLOWPIPE.

the two methods is $\frac{1}{4}$ in. The No. 7 blowpipe was selected on this account, as with it both methods of welding could be investigated. This size also allowed the use of specimens having fairly large cross-sectional areas without the unduly great cost of operation of the larger sizes.

TABLE 1.

SIZES AND CAPACITIES OF FOUCHE BLOWPIPE.

Blowpipe No.	Approximate Thickness of Sheet or Plate, inches	Approximate Consumption, cu. ft. per hour	
		Oxygen	Acetylene
2	$\frac{1}{32}$	2	$1\frac{1}{2}$
3	$\frac{3}{64}$	4	$2\frac{1}{2}$
4	$\frac{3}{32}$	6	$3\frac{3}{4}$
5	$\frac{1}{8}$	10	6
6	$\frac{3}{16}$	16	10
7	$\frac{1}{4}$	25	15
8	$\frac{3}{8}$	36	22
10	$\frac{1}{2}$	45	28
12	$\frac{5}{8}$	65	40
15	$\frac{3}{4}$	100	60

NOTE: For copper plates, larger blowpipes are required than for steel plates of corresponding gauge.

12. *Regulation of the Blowpipe.*—Given the gases supplied under constant pressure, the proper proportioning of the two is obtained by adjustment of the cock C, Fig. 3.

The operator is governed in the regulation solely by the appearance of the blowpipe flame. Slight variations in the proportions caused relatively large variations in the appearance of the flame. This is well shown in Fig. 4, reproduced from photographs of the flame itself. The combustion of acetylene alone (see (a)) gives an intensely white flame of large volume with a heavy formation of soot at its outer end. When oxygen is added, the flame shortens (see (b)) and the combustion is more nearly complete, as is indicated by the nonformation of soot. There is then one small cone close to the tip of the blowpipe which is intensely white. This is surrounded by another white cone which in the cut partially masks the inner cone. Both are perfectly visible to the eye, particularly when observed through blue glasses. Beyond these two white cones is a nearly colorless flame of large volume.

Proper regulation is obtained by reducing the amount of acetylene until only one white cone is visible, as shown at (c), with a colorless flame as before. This single white cone is with the No. 7 blowpipe about $\frac{1}{8}$ in. in diameter and $\frac{5}{16}$ in. long, and has a rounded end. If the acetylene is reduced still further, the cone shortens as shown at (d). Proper regulation is effected when the flame is seen as a single cone of dimensions as large as possible. This is the operator's chief guide. As it is difficult to determine by inspection when this cone has shortened, especially after work has been in progress several minutes, it is convenient to increase the supply of acetylene until two cones appear, then decrease it until the second cone disappears.

References No. 1 and 2 under VI. Bibliography give descriptions of the various flame characteristics and a discussion of the chemistry of the combustion.

III. Test of Welds.

13. *General Plan of Tests.*—As these experiments were undertaken to ascertain the strength of welds as made by a workman of moderate experience, a large number of specimens were prepared for tensile tests. While the statement is often made that the strength of the weld is affected by conditions which are practically beyond commercial control, such as the purity of the gases and the material to be welded, and also, possibly, the construction of the blowpipe, these factors were all disregarded, as they were probably constant in this work and more especially as they duplicated accurately the conditions which exist in commercial work. The skill and care of the operator, without a doubt, are chief factors in controlling the quality of the welds. The effect is especially noticeable when the operator is utterly without experience, as was the case when this work was started. Attention was therefore concentrated on the proper blowpipe manipulation, and the number of test pieces was made great enough to provide considerable practice, which, it was hoped, would show an increase in the strength of the welds as skill was acquired.

The general plan of preparing and testing specimens for tests of strength of welded joint may be seen from Fig. 5. A plate of steel was cut into strips A, B, C, etc., and from the ends of each strip test pieces were cut which were tested in tension to give the strength of the plate material. The remainder of the strip was then cut in two lengthwise. These cuts are shown in Fig. 5 (a), by broken lines lengthwise of the strip. The two parts were then welded together and the welded strip cut across the weld into specimens as shown by the cross-wise lines in Fig. 5. Each strip was about 2 ft. long by 1 ft. wide. In the first series of tests the strips were so arranged that some specimens were cut in the direction of rolling and others perpendicular to the direction of rolling. The specimens were then tested in tension.

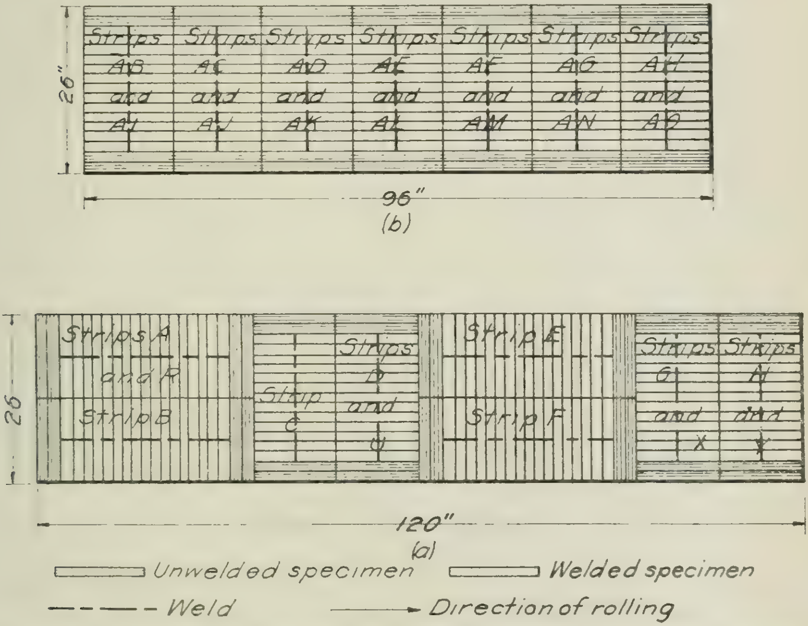


FIG. 5. LOCATION OF STRIPS AND TEST SPECIMENS IN STEEL PLATES.

14. *Preliminary Tests.*—Some welding practice was obtained by welding pieces of band iron 0.135 x 1.344 in.; about 50 such welds were made and tested. The actual blowpipe time required, as computed from the amount of oxygen used, was 2.16 hours.

This band iron, unwelded, had an average ultimate strength of 62 300 lb. per sq. in. and a yield point of 46 400 lb. per sq. in. with an elongation in 4 in. of about 20%. When welded the values for all these properties were lower than in the unwelded material. The loss was about 5.7% in the yield point, 30% in the ultimate strength, and 88% in the elongation. The results of these preliminary tests are not considered of sufficient importance to be recorded here.

This work was excellent considering that the operator had no previous experience and no instruction except that contained in the printed directions accompanying the apparatus. It should also be remembered that the blowpipe was much too large for this thickness of metal so that the material was undoubtedly over-heated.

A. FIRST SERIES OF TESTS.

15. *Specimens.*— The main object in this series of tests was to provide practice in the use of the blowpipe, and to bring out, if possible, the variables affecting the strength of the welds. In general, the efficiency of the welds was found to be low, and a constant effort was made to find the cause of the low strength and its relation to the appearance of black or dark blue spots in the fracture.

Four flange steel plates were secured from Joseph T. Ryerson and Son, Chicago. The plates were 26 × 120 in. and ¼ in. thick. The method of preparing specimens was that described under 13. General Plan of Tests. A whole strip was cut into 16 specimens about 1½ in. wide and 13 in. long, and these were tested in tension to failure. In this way the properties of the weld at every portion of its length were determined. The material would have been injured had the metal been sheared, so the cuts were made on the planer or shaper with a cut-off or parting tool. As this proved to be a tedious job, after the first few strips a power hacksaw was used and proved satisfactory.

For filling, very soft open hearth steel wire No. 14 (0.079 in. in diameter, actual measurement) was used. This was also purchased from Joseph T. Ryerson and Son. The physical properties of this wire, as determined by tension tests, were as follows:

Ultimate strength, lb. per sq. in.,	64 400
Yield point, (about) lb. per sq. in.,	37 500
Elongation in 10 in., per cent,	15
Reduction of area, per cent,	74

No analyses of gas or material were made for this series of tests.

16. *Method of Testing.*—The testing was done in a 100 000-lb. Riehle testing machine having an autographic attachment. The dimensions of the specimens were first carefully taken. A thread micrometer with contact surfaces about $\frac{1}{32}$ in. in diameter was used for obtaining the thickness. Great care was necessary in this measurement, because of the roughness of the surface of the weld when it remained as it came from the blowpipe. The surface of the specimen was divided in such cases into strips $\frac{1}{4}$ in. wide, and the micrometer readings for thickness were taken at the center of each strip and averaged for the thickness of the specimen.

A 6-in. gauge length was laid off each specimen and marked with a center punch. The shortness of the specimens made an 8-in. gauge length impracticable. When placed in the machine, the clamps for the autographic apparatus were secured to the specimen at the punch marks and a record made as the test progressed. From this the yield point and ultimate strength of the specimen were determined with sufficient accuracy for this work. A copy of a number of such records is shown in Fig. 6. The elongations were measured with a steel scale from the specimen after rupture, not from the graphical record.

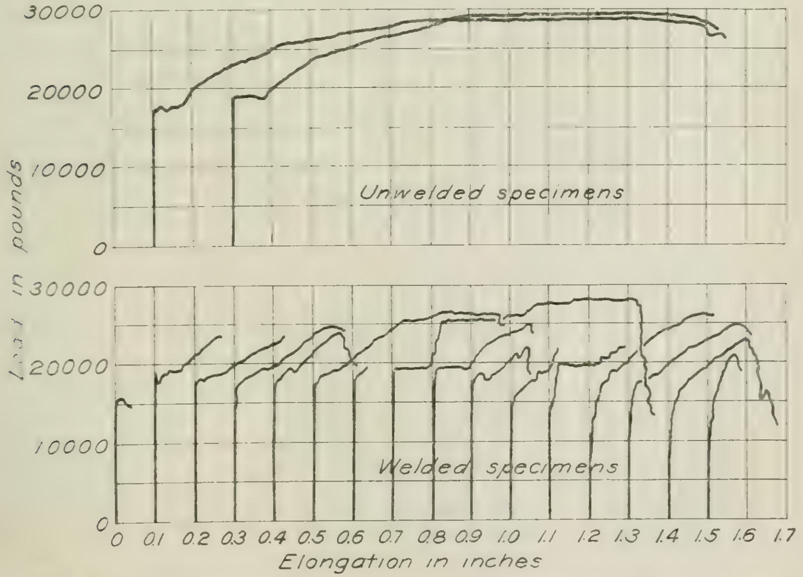


FIG. 6. AUTOGRAPHIC TENSION-TEST DIAGRAMS OF WELDED AND UNWELDED SPECIMENS.

The stresses at yield point and ultimate strength were computed by dividing the load from the graphical record by the actual original area at the place where the rupture occurred, usually at the weld.

The efficiency of the weld was determined by dividing the ultimate unit-stress (when rupture occurred at the weld) by the average ultimate unit-stress of the unwelded specimens, for the same section of the plate. Thus:

$$\frac{\text{Ultimate stress in weld}}{\text{Ultimate stress of unwelded material}} = \text{Efficiency of weld.}$$

This efficiency is then the ratio of the strength of the weld to the strength of the material, and measures, in some degree, the value of the welding process.

17. *Manipulation and Preparation.*—In this, as in the preliminary work, an attempt was made to follow all instructions given in the manufacturer's circular as closely as possible.

These may be summarized as follows:

Commence welding at nearest point and work away from the operator. (See 26. Improvements in Methods of Welding.)

Attend carefully to the regulation of the flame.

The apex of the small flame cone should be in contact with the metal to be welded. (See 26.)

The blowpipe should be held at a constant distance from the work and advanced slowly and regularly with a slight oscillating or circular motion.

When adding metal to the weld, care must be taken not to let the full force of the flame play on the rod or wire unless it is in contact with the pieces being welded which will prevent its being overheated.

Material being added must come in contact only with metal which is fused, otherwise welding does not occur.

The blowpipe was directed against the sides of the joints until the fusion occurred, and the slight circular motion of the flame caused the molten metal to flow together at the bottom. The blowpipe was advanced, still describing small circles, as fast as this weld was formed for an inch or two, then a return was made to the starting place and the metal again brought to a state of fusion. The wire was then fed into the small pool of liquid steel until the blast from the flame threatened to blow it over against comparatively cool steel. The blowpipe was then swung in larger circles which extended the area under fusion somewhat, while allowing the center of the pool to harden. These pools of molten steel were from $\frac{1}{2}$ to 1 in. in diameter. Another pool was then formed just beyond the first so that their edges overlapped. (This method was changed later. See 26. Improvements in Methods of Welding.)

The plates for this series were clamped as shown in Fig. 7, to hold them in their proper relative positions and with their surfaces in the same planes. The thumb-nuts were not tightened sufficiently to prevent the plates from drawing together as the welding proceeded. Unless otherwise stated, the plates were beveled as shown in Fig. 8 (a), and clamped with the edges at one end of the joint in contact, and at the other end ½ in. apart to allow for "creeping". Welding was started at the closed end of the joint. The single strands of soft steel wire, No. 14, were used for filling.

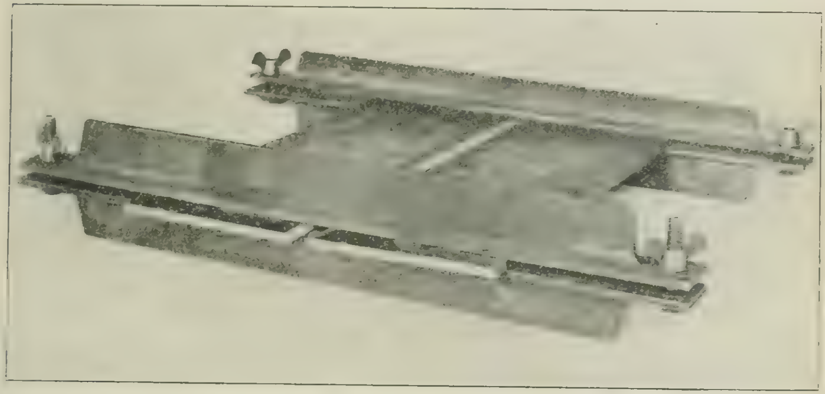


FIG. 7. STRIP CLAMPED READY FOR WELDING.

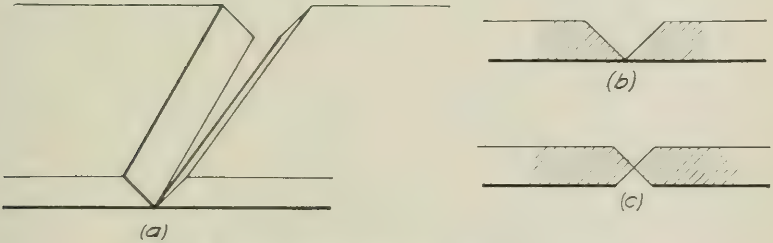


FIG. 8. PLATES BEVELED FOR WELDING.

In adding the wire, difficulty was found in preventing the playing of the full flame on the wire when the blowpipe was given a circular motion; so at times, it was held nearly stationary and the steel wire pushed, as rapidly as it melted, into the pool just beside the flame. Working in this way, it took some time to build up the required thickness of metal at the weld. If depressions appeared after cooling occurred, the surface was again fused and more wire added until, as far as could be determined by inspection, no portion of the welded surface was below the adjacent surfaces of the plates. This series of operations was repeated until the weld was completed.

At times, in welding together the bottom of the groove before adding wire, the metal became too hot and dropped away, leaving an opening which the strong blast of the flame quickly enlarged. In such cases it became necessary to fuse the edges by passing the flame over the opening rapidly, while adding wire as rapidly as it fused, leaving a short length in the opening. When enough metal had been added to prevent the flame from passing through the opening, the whole mass was thoroughly fused together, forming a weld across the bottom of the groove. Wire was then added, as before, to build up the thin place, care being taken not to direct the flame against it too continuously.

The general appearance of such a joint is well shown in Fig. 9 and 10, taken from strip E after welding. Fig. 9 shows the upper side from which the work was done, and Fig. 10 the bottom where the edges were practically in contact before welding commenced. In Fig. 9 the pools forming the weld are shown. They are covered with black oxide formed by the oxygen of the air on the white hot metal left by the advancing blowpipe. The concave centers appear somewhat spongy on the surface but a file shows the bright, clean metal just below. The lighter portions of the plate show the metal which has been heated to redness but not to fusion on each side of the weld. The work proceeded from left to right in this case. In Fig. 10 is again shown the metal which has been heated to redness and also the excrescences of wire and molten metal which passed through gaps in the thin edges. This occurred at about three places in this weld. While not apparent in the photograph, this bottom sagged of its own weight while hot, aided, of course, by the blast from the blowpipe, so that the line of the weld was raised somewhat above the adjacent surfaces thus tending to thicken the metal at the weld. Probably this never exceeded $\frac{1}{16}$ in.

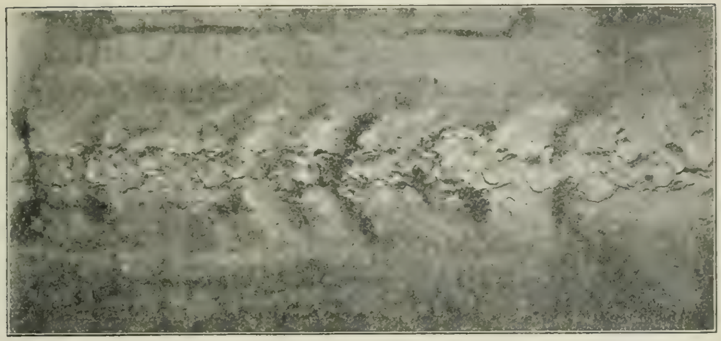


Fig. 9. Upper Side of Weld Made by "Pool" Welding.

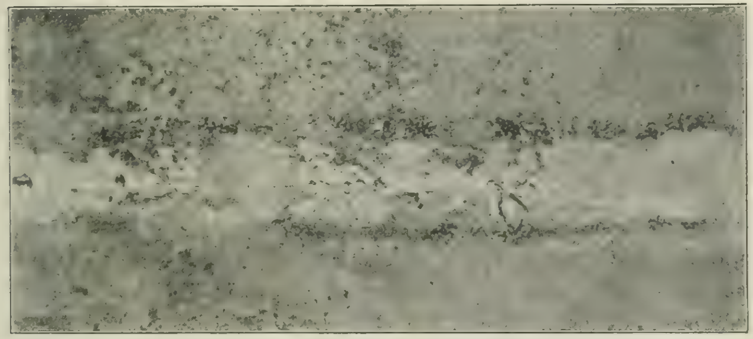


Fig. 10. Under Side of Weld Made by "Pool" Welding.

18. *Strip A.*—In the first strip tested, the general methods of welding, cutting, and testing specimens described in the preceding paragraphs were followed. One of the clamps was removed after the welding had progressed about half the length of the joint. After cooling it was found that the plates had been drawn up at their outer edges on account of the cooling of the comparatively large body of molten metal near the upper surface, so that they formed a shallow trough or V. While the section was almost flat where the welding started, on account of its having cooled while held by the clamp, at the other end of the weld where the clamp had been removed, the sides were fully an inch above the joint.

While the welding had been in progress, the edges had been drawn together just ahead of the blowpipe by the cooling of the joint just back of it. The amount allowed for this "creep" ($\frac{1}{2}$ in.) was hardly sufficient, as the thin edges appeared to crowd, thus tending to overlap. The strip was cut into specimens and these were tested without being straightened, although severe bending stresses were undoubtedly imposed on the material on the concave side of the specimen, thus tending to lower the strength of the weld. The data for these specimens are given in Table 2. The appearance of the metal in the welds after rupture is shown in Fig. 11. In most cases the silky fracture of the unwelded specimens is altered to crystalline in the welds, probably on account of the rapid cooling from a liquid state without rolling or other working of the metal. At intervals dark spongy spots, black or blue in color, occur in the weld. When questioned regarding them, the blowpipe manufacturer claimed that any discoloration must be due to burnt metal caused by an excess of oxygen in the welding flame.

The average efficiency of these specimens was 69.3%, the highest, 90.7% and the lowest 47.7%. A gradual decrease was noted as the welding of the strip progressed, due, very probably, to the fact that specimens were not straight when tested, although the data are insufficient to verify this.

For specimens having an ultimate strength below that of the yield point of the material, the weld fails before the material in the remainder of the specimen is stressed to the yield point. Although the material in the weld is probably somewhat brittle, it is so small in amount that little or no elongation would be observed on a 6-in. gauge length even if it were as ductile as the remainder of the specimen.

When the strength of the weld is above the yield point of the material, then the material throughout the length of the specimen elongates until the rupture occurs. This rise in the elongation was very noticeable for specimens 6 to 9, inclusive, for strip A.

The length of the welded portion is so small in comparison with the length of the specimen that the yield point at the weld could not be determined with accuracy, and hence the yield point of the welded specimen is not considered especially significant.

19. *Strip B.*—The preparation and manipulation used for strip A were followed as closely as possible for strip B, except that the allowance for "creep" was $\frac{5}{8}$ in. instead of $\frac{1}{2}$ in. This was found to be too much, as the plates did not draw together sufficiently to close the bottom of the groove, and consequently the flame melted through at frequent intervals.

When the weld was about half completed, work was stopped to lengthen the thread on one of the thumb bolts. This allowed the plates to cool and they warped and twisted badly. The unwelded edges of the groove overlapped about $\frac{1}{2}$ in. at the further end of the section so that satisfactory completion of the weld was impossible. The specimens were cut from the good weld and tested as before. The data are given in Table 2.

The average efficiency was 68%, the highest 79% and the lowest 56.3%.

20. *Strip C.*—This strip was welded in the same way as the two previous strips. The allowance for "creep" was $\frac{1}{2}$ in. and the section was practically flat when cold. The rough surfaces of the welds were ground practically smooth on an emery wheel before measuring the thickness. The width was divided into three strips, each about $\frac{1}{2}$ in. wide, and the thickness was measured at the middle of each as before. All welds in this strip and in all strips later tested, unless otherwise stated, were ground smooth, as by so doing the area of the weld could be more accurately determined. The emery wheel was of a medium coarse grade and used dry but the specimens were cooled frequently in water and some care was taken not to heat them enough to cause much "bluing" of the steel surface, as an annealing effect upon welds might result. See Table 2 for data.

The average efficiency was 74.3%, the highest 90.5% and the lowest 52.7%.

21. *Strip D.*—This strip was welded as usual except that an attempt was made to determine the effect of variations in the flame regulation, which were intentionally made excessive. The allowance for "creep" was $\frac{9}{16}$ in.

Specimens No. 5 to 8, inclusive, were welded with the regulation as perfect as possible, while for 9 to 12, inclusive, there was a decided excess of acetylene, and for 13 to 15, inclusive, a decided excess of oxygen. In the second lot, the second cone of the flame, Fig. 4b, was, as nearly as could be judged by the eye, 150% of the length of the first cone, both being measured from the blowpipe tip. In the third lot, the first cone, Fig. 4 (d) was shortened to little more than 50% of its length when properly regulated. Fig. 4 (c) shows the flame properly regulated. See Table 2 for data.

The average efficiency was 64.5%, the highest 79% and the lowest 52.7%.

22. *Strip E.*—As the effect of varying the regulation of the blowpipe with the previous section did not appear to have a marked influence upon the strength of the weld, it was decided after some consideration that possibly the single strands of No. 14 wire which had been used for filling up to this time, might become overheated in the blowpipe flame and thus be the cause of the burnt spots and the low strength. In order to try a larger cross-section of filler rod, four strands of wire were twisted tightly together for this section. This gave a large surface exposed to the action of the flame so that melting occurred rapidly, but at the same time gave a larger body of metal to absorb the heat and fill the groove rapidly. See Table 2 for data. Specimen No. 12 broke 2 in. from the weld.

The average efficiency was 69.2%, the highest 80.5% and the lowest 54.6%.

23. *Strip F.*—The allowance for "creep" was ½ in. Four-strand filling was again used. As in previous work, the blowpipe tip became heated from the weld, as the tip of the flame was kept approximately in contact with the surface of the metal. A gradual increase in the amount of acetylene for proper regulation was found necessary, due to this increase in temperature. Several times the acetylene cock was open wide so that further regulation was impossible. When this occurred, the blowpipe was cooled in water which restored the original conditions as regards regulation. Upon the whole, the flame regulation for this section was quite poor.

The surface of the welds was purposely not ground, in order to avoid any annealing effect due to the heating caused by the dry emery wheel. See Table 2 for data. The low percentage of elongation for the unwelded specimens is due to the fact that they all broke outside the gauge length.

The average efficiency was 66.8%, the highest 74.9% and the lowest 55%.

24. *Strip U.*—As the welds with beveled edges did not increase noticeably in efficiency, a butt weld was tried. This strip had square edges which were practically in contact along the seam before welding. This may be expressed by saying that the edges of the plates were beveled at 90° instead of 45°, as in previous strips. No filling material or wire was added.

The plates were clamped as usual with no allowance for "creep," as it was supposed that the square edges would prevent any tendency to overlap due to the contraction of the metal in the weld. This, however, proved to be an error. After the weld was finished and the plates cooled, they were found to be badly warped. When three corners were on a plane surface, the fourth was about one inch above it. They had also crowded together so that while the weld started with the surfaces of the plates flush, after about two-thirds of the weld had been completed they were offset $\frac{1}{8}$ in. and at the end offset $\frac{1}{16}$ in. The end was, of course confined closely by the clamp there. Evidently allowance should have been made for creep.

The welding was performed by causing fusion of the metal on one side only of the seam and causing the metal to flow together by the blast of the flame as it was swung back and forth. The metal was melted as deep as seemed possible and left rough with no attempt to add metal or grind the weld.

The flame was well regulated throughout, as it was frequently adjusted and never became hot enough to require cooling. After the weld was about half complete, the regulation remained practically constant until the work was finished. With the beveled seam the blowpipe tip becomes highly heated, due to the reflection from both sides of the groove. With the butt weld the blowpipe was further from the metal, generally, and maintained its regulation after reaching an approximately constant temperature. See Table 2 for data and Fig. 11 for appearance of fracture. Fig. 11 shows very clearly that the welds extended only a little way below the surface of the plates. The metal which has been melted shows a coarse crystalline fracture. Below that is a band of white metal which probably became pasty in welding but did not fuse thoroughly. This metal appears to unite to a slight extent but the weld there is weaker than through the molten metal. Below this, again, is a band of dark metal which was unaffected by the flame but was heated enough to oxidize on the surface wherever exposed to the air. The ragged appearance of this band, as in specimen 6, was due to a slight tearing of the metal surface by the dull cutting-off tool. Whereever this dark band appears on only one of the two pieces for each specimen, as in 13 and 14, it shows the amount of-offset as explained above.

The average efficiency was 54%, the highest 74% and the lowest 35.1%. Considering the small areas actually fused and welded, this seemed quite remarkable.

25. *Strip Y.*—The allowance for creep was $\frac{5}{16}$ in. The plates were squared and the other conditions were the same as in strip U. They were welded from both sides without the addition of filling material.

The blowpipe was well regulated, particularly as the acetylene was readjusted to make sure of proper regulation after completing about 2 in. of weld. See Table 2 for data and Fig. 11 for appearance of fracture. As in the previous strip the band of white, noncrystalline metal through the middle of the fractures probably shows metal which was not melted.

A great increase is shown in the strength of the welds as work proceeded, but this may partly be accounted for by possible errors in measuring the thickness of the weld. The rough surfaces of the weld made accurate readings of the thickness impossible. As there was a tendency to measure the least thickness near the desired point, the average thickness and consequently the area are probably too low, thus causing the calculated stresses to be high proportionally.

The average efficiency was 82.4%, the highest 118% and the lowest 43.5%.

26. *Improvements in Methods of Welding.*—An engineer for the blowpipe manufacturers, Fred W. Wolf, Jr., was present when some of the specimens from the last three strips were tested. He discussed methods of welding and demonstrated the use of the blowpipe. Some days later, further instruction was obtained from an experienced welder employed by the same company.

While the manipulation used in making the welds up to this time was satisfactory, there were some ways in which the work could be more easily performed. It appeared likely that the adoption of such changes would also result in increased efficiency of the welds. These points may be briefly summarized as follows: Some workmen have found it preferable to work toward the operator rather than away from him, as was done in these welds. In working away from the operator, almost necessarily the blowpipe flame is directed toward the unwelded portion of the plates, making, perhaps, an angle of 60° with the completed weld. The blast from the flame tends to force melted metal from the end of the weld over upon colder metal with which it does not unite and to make it difficult to build up the filling material to the required thickness.

If, instead, the work progresses toward the operator, the blowpipe being held as described above, except that the blowpipe head makes an angle of about 120° with the finished portion of the weld, the flame strikes the sloping surface of the molten metal at the end of the weld more nearly perpendicularly and has less tendency to displace this metal.

Instead of welding in the bottom of the groove for a short distance, then forming a pool of molten metal of the required depth above it, it seems preferable to add constantly very small portions of the filling wire to the advancing surface of melted metal in the groove. If the work is done toward the operator, this procedure is comparatively easy. The sides and bottom of the groove become melted by the time the weld reaches them and the filling wire can be added uniformly to the comparatively small area of molten metal forming the end of the weld. This area advances, gradually, parallel to itself at all times, which was not the case when pools were formed.

To assist in keeping the molten metal in place, the plates may be inclined upward in the direction in which the weld is advancing. A rise of about an inch to the foot is sufficient.

Instead of keeping the tip of the flame constantly in contact with the molten metal it is advisable to increase the distance. If removed too far, the metal will not melt rapidly, and satisfactory work is impossible, so that experience shows that it is desirable to bring the flame in contact with the metal when working on cool metal, then gradually to withdraw the flame as long as satisfactory progress is being made.

Trial showed that the modified methods of carrying on the work aided considerably in *making* the welds, at least, and they were used in subsequent work. Often, after welding had started, and the metal became well heated, the flame could be removed from the work so that the distance from the tip of the flame to the metal was about equal to the length of the first cone. This apparently had no effect upon the progress of the work from the standpoint of rapidity of fusion, and did have two advantages. On account of the increased distance from the hot metal, the blowpipe did not become so highly heated, and after a short time maintained such a temperature by radiation, etc., that practically constant flame regulation was preserved. Frequent cooling of the blowpipe in water was therefore unnecessary; consequently, there were fewer interruptions to the work.

The greater distance from the metal also decreased considerably the number of "back fires", or small harmless explosions within the blowpipe. This will be evident when it is explained that the acetylene and oxygen unite to form an explosive mixture within the head of the blowpipe, but, as a rule, burn only upon issuing from the tip of the blowpipe. If the gases within the mixing chamber were stationary, the flame would be transmitted backward at a definite rate through the tip of the blowpipe and would cause an explosion or "back fire" in the mixing chamber of the blowpipe. The gases then continue to burn within the mixing chamber if oxygen and acetylene are supplied. Usually, however, the velocity of the gases out through the blowpipe tip is greater than that of the propagation of the explosion back into the mixing chamber, so that the gases burn quietly outside the tip. A "back fire" is caused by reducing the velocity of discharge through the tip, usually by obstructing the opening, as when the blowpipe is passed too close to the weld or other object. Increasing the distance of the blowpipe from the weld makes it much easier to avoid "back fires" from this cause.

Previously, when a "back fire" occurred, the acetylene was shut off, a procedure which in a few seconds extinguished the flame within the mixing chamber and allowed the blowpipe to be relighted. By observing an experienced operator, it was found that all that was necessary to extinguish a "back fire" was to close the tip completely for an instant, by brushing the tip across the clothing, then to relight the blowpipe by directing it upon the hot metal in the weld. This procedure reduced the interruption caused by a "back fire" to a second or so, at most, during which the metal scarcely cooled at all, while previously it often became very dark red, requiring some time to bring it again to the welding temperature. This cooling probably had a detrimental effect upon the strength of the welds.

27. *Strip G.*—In the tensile tests of specimens from strip G and in subsequent tests, instead of making an autographic diagram for the test of each specimen, the reading for ultimate strength was taken directly from the beam of the testing machine as usual, which effected a saving of time. The yield point for the welded specimens was not observed, as it appeared to depend entirely upon the yield point of the material outside the weld and to have no bearing upon the efficiency of the welds. Photographs of the specimens were also omitted as being unnecessary at this point in the work.

The allowance for creep in strip G was 0.4 in. The plates were beveled at 45° and four-strand No. 14 wire for filling used as for previous strips. A portion of these plates was used in demonstrating the rapidity of the modified methods of welding and was removed before making this weld. The surface of the weld was ground to obtain an approximately smooth surface. See Table 2 for data.

The average efficiency was 69.6 %, the highest 75.3% and the lowest 61.2%.

28. *Strip H.*—The allowance for creep was 0.45 in. The plates were beveled and ground after welding as for the previous strip. Instead, however, of using No. 14 wire for filling, a sample of $\frac{1}{8}$-in. soft iron wire supplied by the blowpipe manufacturers was used. See Table 2 for data. Apparently this $\frac{1}{8}$-in. wire did not make as strong a weld as the No. 14 used for the previous strip, but there were probably other conditions which affected the results.

The average efficiency was 50.6 %, the highest 58.9% and the lowest 41%.

29. *Strip R.*—The allowance for creep was 0.8 in., and three strands of No. 14 wire used for filling. Otherwise the conditions were the same as for the preceding strips. After welding the plates for about 12 in., it was found that the plates were separated by a gap which it was difficult to bridge with the filling material. Work was then stopped, and only the welded portion tested. See

Table 2 for data.

The average efficiency was 76.7 %, the highest 86.9% and the lowest 68.5%.

30. *Strip X.*—The allowance for creep was ½ in., otherwise conditions were the same as for the preceding strip. See Table 2 for data.

The average efficiency was 73.9 %, the highest 85.5% and the lowest 56.6 %.

TABLE 2.

RESULTS OF STRENGTH TESTS OF WELDS —FIRST SERIES.

Strip	Efficiency per cent			Rate of Welding ft. per hr.
	Av.	Max.	Min.	
A	69.3	90.7	47.7	1.47
B	68.0	79.0	56.3	....
C	74.3	90.5	52.7	....
D	64.5	79.0	52.7	1.00
E	69.2	80.5	54.6	....
F	66.9	74.9	55.0	2.80
U	54.0	74.0	35.1	....
Y	82.4	118.0	43.5	2.84
G	69.6	75.3	61.2	4.17
H	50.6	58.9	41.0	0.80
R	76.7	86.9	68.5	1.50
X	73.9	85.5	56.6	2.50

31. *Summary for First Series.—Grinding the Weld Surface.*—The necessity for removing the rough surface of the weld became very apparent when specimens from strip Y seemed to give over 100 % efficiency. A comparison of the range in efficiency for each section shows that upon the average ground specimens showed less variation than the unground. The unground strips are A, B, F, U, and Y, and their average range in efficiency, found by subtracting the lowest efficiency from the highest, is 39.8%. The ground sections are C, D, E, G, H, R, and X, and their average range is 22.2 %, only 56 % of range of the unground.

As explained for strip Y, when the weld was rough as left by the blowpipe, the constant tendency was to measure the least thickness near the point where a reading was to be taken. This, without doubt, frequently gave a sectional area less than the actual, and a consequently higher efficiency on the average for the unground specimens. The grinding introduced another factor into the problem whose influence upon the welds was unknown. If means were provided for milling the surfaces smooth, the temperature would probably never rise enough to cause any annealing effect. As care was taken in grinding to cool the specimen frequently, there is only a slight chance for annealing in these specimens.

32. *Consumption of Oxygen and Acetylene.*—The pressure gauges attached to both acetylene and oxygen tanks enabled the amount of gas consumed for each section to be computed. Readings of these gauges were taken during the welding of many strips. The amounts of acetylene and oxygen consumed were determined and compared with the average value for a No. 7 blowpipe given in the catalog of the blowpipe manufacturers. The measured average consumption of oxygen was 20.6 cu. ft. per hr. while 25 cu. ft. is given as the consumption in the catalog. The acetylene consumption was 22.7 cu. ft. per hr. and the catalog value is 15 cu. ft. The rather wide difference between the measured value and the catalog values and more especially the erratic fluctuations in the oxygen rate measured by gauge readings lead to the conclusion that while the pressure gauges are sufficiently accurate to determine the volume of gas contained in the tanks at any time, they are not sufficiently accurate (or sensitive) to determine the gas used for time intervals, say, of one hour. More accurate measurements were made in later tests. This subject is discussed in IV. Tests of Gases and Flame Regulation. The ratio of acetylene to total gas volume was also determined from the gauge readings and an average of 56.3 % found, which is much higher than the ratio of 37 % usually given, (1 volume of acetylene to 1.7 volume of oxygen). The ratio of the gas rates in the catalog is almost the same as this latter value, being 38.5 %. The wide fluctuations in the measured value of this ratio indicate that the tank gauge readings are wholly unreliable for determining this ratio or computing the quantity of gas used. Other means were therefore employed later.

33. *The Welding Rate.*—The rate of welding, of course, varies considerably with the skill of the workman and the conditions under which the work is done. The rates for the several strips are plotted in Fig. 12, and as might be expected, show an increase in speed as experience was gained.

In no case was the catalog value of 5 ft. per hr. reached, but it appears reasonable that an average, experienced workman could maintain that speed for several hours if not for the whole working

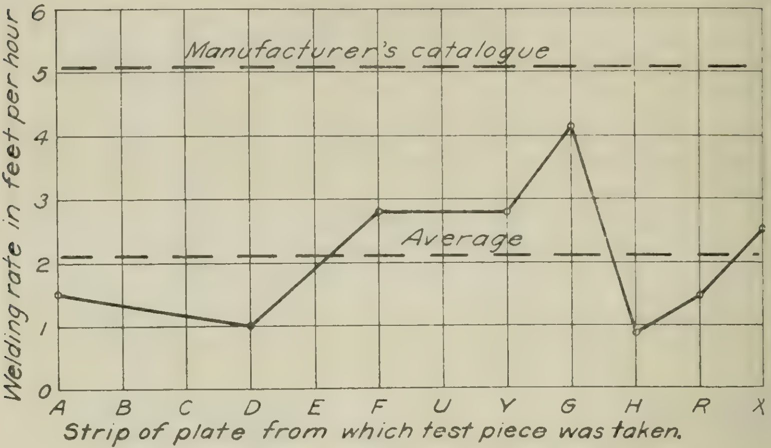
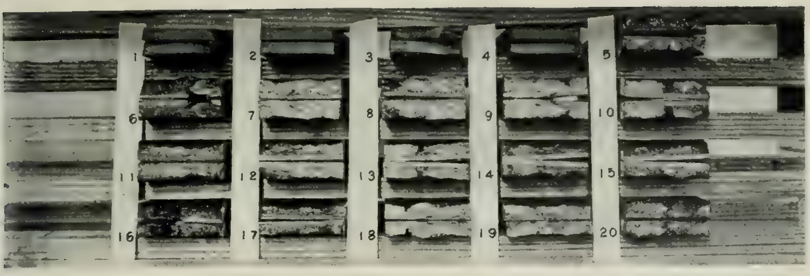


FIG. 12. RATE OF WELDING—FIRST SERIES.

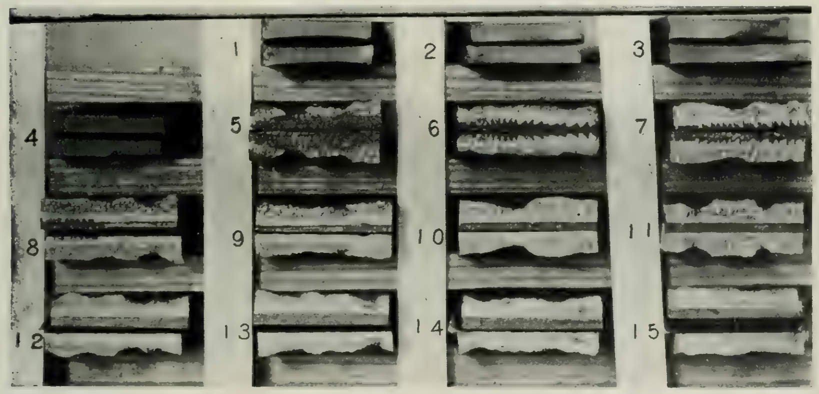
day. It should be noted that considerable instruction was received after strip Y was welded and that the method of working was changed considerably at that time. If the rate for strip G is excepted (possibly in error) the remaining strips, H, R, and X, show a return to about the original welding rate of one foot per hour with a much more rapid rise in the rate than was the case with the first strips. With continued practice, the catalog rate of 5 ft. per hr. would probably be reached.

It will also be noticed that the rate for strip Y, which was a butt weld, fused from both sides, is about the same as for strip F which was a beveled weld with wire filling. In both cases fusion occurred throughout the weld so that one method appears to permit about the same welding rate as the other.

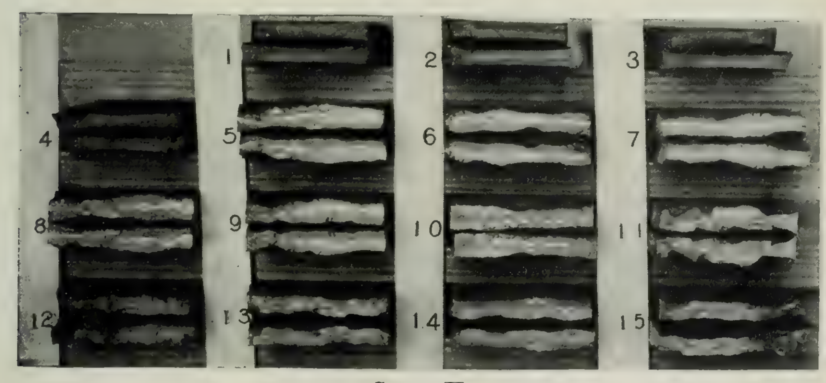
While too great reliance should not be placed upon these welding rates, either as to their accuracy or the ability of another workman to equal them, they do show that a moderate rate of welding, say, 2 to 3 ft. per hr. with $\frac{1}{4}$-in. steel plates, can be obtained with comparatively little practice. The total length of weld in these 12 specimens was about 24 ft. which at the average rate of welding of 2 ft. per hr. could be completed in 12 hours of blowpipe work. This tends to confirm the statement that some commercial shops train inexperienced men in two or three days to reasonable proficiency with the blowpipe and employ them upon their own work afterwards.



STRIP A.



STRIP U.



STRIP Y.

FIG. 11. FRACTURED SURFACES OF TEST SPECIMENS, (SPECIMENS NO. 1, 2, 3, AND 4 ARE UNWELDED).

34. *Allowance for Creep.*—The values are shown in Table 3 for the allowance for creep in per cent of the length of the weld.

TABLE 3.

ALLOWANCE FOR CREEP OF WELDED JOINTS

Section	Approximate Length of Weld, inches	Allowance for Creep, inches	Per cent	Remarks
A	27	½	1.8	Rather small
B	27	⅝	2.3	Too much
C	20	½	2.5	
D	20	9/16	2.8	
E				
F	27	½	1.8	
U	20	None		Too small
Y	20	5/16	1.6	
G	20	0.4	2.0	
H	20	0.45	2.3	
R	27	0.8	3.0	Too much
X	20	½	2.5	

The average of those allowances which appeared to be satisfactory is 2.2 %; not much less than the 2.5 % recommended by the blowpipe manufacturers. If the allowance is too small, the thin edges of the plates crowd together more or less with no bad results, but if the edges fail to meet or nearly so, it is almost impossible to weld at a satisfactory rate.

35. *Properties of the Steel Plates.*—Of the strips welded, A, B, E, F, and R, were cut into specimens perpendicular to the direction of rolling, and strips C, D, U, Y, G, H, and X, were cut into specimens parallel to that direction. The material, as shown by averaging the tests of the unwelded specimens from each strip, had the properties shown in Table 4.

TABLE 4.

PROPERTIES OF STEEL PLATE—FIRST SERIES

	No. of Specimens	Yield Point lb. per sq. in	Ultimate lb. per sq. in.	Elongation in 6-inch gauge length per cent
Perpendicular to rolling	20	40 800	65 500	19.0*
Parallel to rolling	28	39 900	63 000	23.8*
Average		40 350	64 250	21.4

*These values include 12 specimens perpendicular to rolling and 16 specimens parallel to rolling.

No elongation was recorded for the remaining specimens of each group.

Strips G to X, inclusive, were welded after instruction and the adoption of modified welding methods. As a result the efficiencies rose, say, from 70 % to 75 %.

The variation from the average efficiency, in these last strips, is small enough to show, with the somewhat increased average, that the newer method of working was an improvement over the old, but it seemed that some precaution might have been neglected which would increase the efficiencies considerably. Inspection of the fracture of specimens welded by the modified method showed a decrease in the amount of black or blue discoloration of the metal, although there was still more than could be wished. Possibly the effect of this discoloration is shown in the low efficiencies.

B. SECOND SERIES OF TESTS.

37. *Blowpipe.*—The work of the second series was a continuation of that of the first under somewhat altered conditions. An effort was made to determine the variables affecting the efficiency of the welds, with some success for the last few strips of the series.

In place of the blowpipe used in the first series a recent form of the Fouché blowpipe was obtained which was provided with a number of interchangeable heads, in this case corresponding to the heads of blowpipes No. 3, 4, 5, 6, 7, and 8. The size best suited to the work could be quickly fitted to the blowpipe body, the result being an apparatus somewhat lighter than the design previously used but one operated in the same way. The general appearance of this blowpipe is shown in Fig. 3, (p. 12), the heads for it standing in a row at the right.

38. *Filling Wire, and Its Effect on Welds.*—Special wire, recommended by the blowpipe manufacturers, was obtained from John A. Roebling's Sons Company, 171 Lake Street, Chicago. This was designated by them as $\frac{1}{8}$-in. diameter, liquor finished, bright, annealed, genuine Norway iron wire. Tension tests of several samples gave the following results:

Ultimate strength	50 000 lb. per sq. in.
Yield point, about	31 000 lb. per sq. in.
Elongation in 10 in., per cent,	20
Reduction of area, per cent,	67

After being cut into lengths of about 6 ft., this wire was coiled, as shown in Fig. 3, so as to be readily held in the hand. Each coil was about sufficient for welding one strip of $\frac{1}{2}$-in. steel, 20 in. long. This wire melted readily and in general worked satisfactorily. The most noticeable difference between it and the No. 14 steel wire used up to this time was the absence of mill scale. If bent, the steel wire showed a coating of scale, or oxide, which flaked off. The iron wire, however, had been pickled or otherwise treated to give a clean metallic surface. When melted by the blowpipe, the steel wire showed a surface of moderate incandescence covered by irregular spots which were much brighter. While the general color appeared bright red through blue goggles, the spots seemed white hot. The red mass appeared quite firm, flowing reluctantly under the pressure of the blast from the blowpipe. The white material, on the other hand, seemed quite fluid and formed constantly changing figures on the red surface. Under the continued action of the blowpipe, it tended to gather into small globules. The impression formed as one watched it was that this material gradually decreased in amount under the blowpipe, but possibly its disappearance was due to its being driven on to comparatively cool metal where it was less visible. It seems probable that the red material was filler, fused without change, and the white hot material a film of oxide over it, as the behavior of each agreed with our general knowledge of these substances, especially that pure iron is melted with difficulty while the oxide melts at a much lower temperature. Possibly the oxide, if it is such, is reduced to metallic iron by the blowpipe. This would account for the disappearance of the oxide.

The steel wire, after each addition of material to the weld, showed half or two-thirds of the red area covered by the white, while the iron wire showed much less, possibly a quarter as much. In either case, some care was taken to continue the action of the blowpipe until the oxide had almost or entirely disappeared before adding more filler. Perhaps this was unnecessary, as the metal added may work down under the oxide; if, however, this does not occur, inclosing oxide in the weld must, necessarily, reduce its strength and efficiency. Possibly, dark spots in the weld after rupture are inclosed oxide.

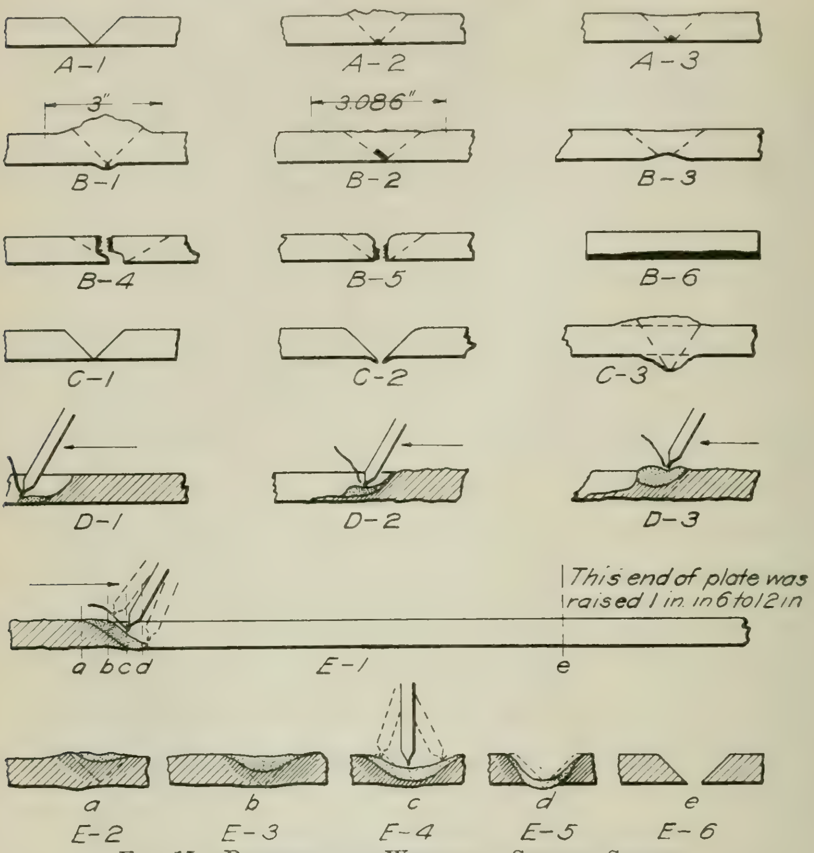


FIG. 15. PROGRESS OF WELDING—SECOND SERIES.

39. *Material and Preparation of Specimens.*—Instead of the ¼-in. plates used for the first series, similar sheets from the same firm were obtained which were ⅛-in. in thickness. Plates of this thickness seem better suited for practice welding and experimenting than either thicker or thinner ones. Each plate was divided into strips, as shown in Fig. 5 (b), so that all specimens lay with their longest dimension parallel to the direction of rolling. The strips were cut as for the first series, except that a sharp power shear was used instead of the cutting-off tool.

All strips were beveled at 45° as shown at A-1, Fig. 15. This was done on a dry emery wheel as the amount of metal to be removed was not large. Each section was clamped, as usual, and welded by fusing in a $\frac{1}{8}$-in. iron wire, using the No. 5 head fitted to the blowpipe.

The pressure under which oxygen was supplied to the blowpipe was 12 lb. per sq. in. The acetylene pressure averaged 11.8 in. of water and varied from 11.5 to 12.75 in. As slight variations in these pressures probably had little or no effect on the flame regulation or the welds, they need little consideration.

A cross-section through the weld is shown at A-2, Fig. 15. As is the case with all the sketches in Fig. 15, an attempt is made to show the general features of the weld under discussion, not to represent them accurately to scale, which would be difficult if not impossible. Many are exaggerations, more or less crude, of the phenomena they are intended to illustrate.

All specimens were cut from the strips with the power hack saw, as before, and the surface of the weld ground, as shown at A-3, top and bottom, on a dry emery wheel, to give a reasonably smooth surface. In many cases the thickness through the center of the weld was slightly less than that of the plate.

40. *Manipulation.*—For all of the strips of the second series the welding process used for the last of the first series was employed, the pool system of welding used at first (described on page 18) having been discarded. The difficulties involved in the pool system and in working away from the operator can better be understood by reference to D, Fig. 15. In the diagram, comparatively cool metal (black hot) is represented by coarse cross hatching, or is left unshaded; metal heated to redness, by close cross hatching, and molten metal is represented by a dotted surface. The arrows indicate the direction in which the weld is progressing. In the pool method the bottom of the groove was first welded for a short distance (See D-1) by melting down the sides of the groove (see E-5) and adding some filler. The thickness was then increased by a pool (See D-2) to the required thickness of the plates (see D-3). Working in this way it was somewhat difficult to prevent the filler cooling on metal imperfectly fused.

The method used for the welding of the second series is shown in Fig. 15. A longitudinal section along the weld is shown at E-1, and cross sections through several points at E-2, E-3, E-4, E-5, and E-6. The weld was built up by means of additions of melted filling wire at the front of the work, regularly, so that the surface advanced along the groove approximately parallel to itself. The bottom of the groove was closed by material from the sides of the groove and from the filling wire, (see E-5); then the thickness of metal was gradually increased until somewhat greater than that of the surrounding plates. As each drop of melted filler reached its place, the blowpipe was directed against it until it spread out over the molten material below and lost its outline. The oxide on the surface was driven off before more filler was added. Usually the distance from the flame to the metal was 50% to 100% of the length of the first cone.

41. *Strip AB.*—Only one clamp was used for this strip and it was applied at the raised end opposite that where welding started. The thin plates sagged, one more than the other in places, which made an offset in the weld, reducing its area.

The fractures showed a rather dead or dull gray surface, slightly spongy, with small dark spots at intervals. See Table 5 for data.

The average efficiency was 72.1%, the highest 77.9% and the lowest 62.5 %.

42. *Strip AC.*—Both clamps were used as in the first series, preventing sagging somewhat. On account of the small allowance for creep, the plates overlapped so that satisfactory work was impossible. The weld was carried within about two inches of the end of the seam but only about the first 13 in. was cut into specimens. Of these, only the following three, No. 10, 11, and 12, were welded on both sides in an attempt to fill up the angle due to the offset.

The fractures were similar to those for strip AB. See Table 5 for data. A rise in strength was noted for specimens No. 9, 10, and 11, due probably to welding both sides of the plates. Specimen No. 11 broke first outside the weld; then, when retested, in the weld. The greater load was used in computing the stress on the cross sectional area of the weld, and this applies to all specimens of this series which were retested to cause rupture in the weld.

The average efficiency was 69.1 %, the highest 82.0% and the lowest 54.4 %.

43. *Strip AD.*—Satisfactory allowance for creep ($\frac{1}{2}$ inch) was made for this strip and the weld completed. Some offset occurred due to sagging of the plates, but they were welded from one side only.

The fractures showed some dark spots in the dull gray, spongy surface and also a few crystalline spots at intervals. See Table 5 for data. A rather remarkable increase occurred in strength as work progressed along the weld.

The average efficiency was 78.2 %, the highest 94.8 % and the lowest 72.0 %.

44. *Strip AE.*—To prevent sagging of the plates when heated, the clamps previously used were bolted up on pipe spacers, as shown in Fig. 3. These spacers held the lower T-sections of each clamp in a definite relation to each other. The plates were then clamped with the clamps parallel to the weld. This arrangement kept the plate surfaces nearly in the same plane—an important matter with thin plates—so that the weld has nearly the cross sectional area of the rest of the specimen.

The fractures showed generally a clear gray surface with a slight spongy appearance. There were very few dark spots. See Table 5 for data. Great strength was shown by specimens No. 8, 9, 10, and 11. This is partly explained by the fact that all others had a band of metal about $\frac{1}{32}$ in. wide at the bottom of the weld which appeared to be poorly welded. Possibly fusion did not take place there.

The average efficiency was 75.6 %, the highest 90.0 and the lowest 59.9 %.

45. *Strip AF.*—The clamp used for strip AE was improved by welding the spacers and bolts to the T-sections, making the clamp stiffer. The upper T's were then removed and the bearing surfaces, for the plates, finished in the shaper. This assisted greatly in bringing the plate surfaces into the same plane and avoiding offset in the weld. This clamp was used for all subsequent work for this series.

The fractures showed a bright surface with almost no dark spots. While it tended toward dull gray, it was not spongy. Specimens No. 6 to 10, inclusive, had a gray surface with crystalline spots while No. 11 to 16, inclusive, were largely crystalline. Specimen No. 17 showed a dark band across the weld. See Table 5 for data. An increase in strength was shown by specimens with crystalline fracture.

The average efficiency was 72.0 %, the highest 87.4 % and the lowest 44.8 %.

46. *Strip AG.*—As the strength of the welds up to this time had shown little increase, the molten metal for strip AG was hammered frequently as it was put into place. A small riveting hammer was used, having a handle 11 in. long, and a head weighing 11.5 ounces. After extending the weld about $\frac{1}{4}$ in., 10 to 15 light blows, (2 in. stroke) were delivered rapidly upon the sloping surface at the end of the weld. During this time the metal usually became very dull red and required some time to bring it to the fusion temperature again.

The fractures showed no crystals but rather a dull gray spongy surface, covered by many dark spots. These, perhaps, aggregated a quarter of the total area. See Table 5 for data. The wide and erratic fluctuations in strength lead to the conclusion that alternate hammering and welding do not produce uniform work. The fact that the average efficiency was lower than for any strip so far in this series also throws doubt upon its value. It is difficult to see how hammering can increase the density of metal which is immediately afterwards heated to fusion to continue the weld. The amount of work required of the operator is largely increased, as well as the time.

The average efficiency was 64.4 %, the highest 76.8 % and the lowest 50.9 %.

47. *Strip AH.*—A gasoline torch was used to preheat the beveled edges of the specimens of strip AH. Its flame was directed against the seam, from below, an inch or two in advance of the end of the weld. This did not interfere with the welding as the blowpipe was used from above as usual. The torch supplied enough heat to bring the bottom of the groove to redness, which reduced, considerably, the time required to melt the metal. The preheating also noticeably increased the allowable freedom in using the blowpipe. It could be swung over a greater area of weld and also be held at a greater distance; moreover, the filler flowed quickly into the weld. Though the welding rate is lowered, rather than raised, delays due to stopping the work entirely are included so that the rate, as given, is incorrect. A rough estimate would put the rate of welding for preheated plates about twice that for cold ones. The rapidity and ease with which the filler united with the weld would lead one to think, also, that great strength should result.

Work progressed continuously until specimens No. 5 to 11, inclusive, had been welded, then there was a delay of a minute or more to pump up the pressure in the gasoline tank of the torch. Specimens No. 12, 13, and 14, were next welded; then the gasoline became exhausted, making it necessary to complete the weld without preheating. This portion includes specimens 15,16,and 17.

It had been noticed that many of the preceding welds showed after rupture a narrow strip just at the bottom of the groove which apparently was poorly welded. This defect is indicated in A-3, Fig. 15, by a black spot which the usual grinding of the weld surface did not remove. After rupture, the fracture presented the appearance shown in B-6, which is a cross section of the specimen. The band of poor welding, shown in solid black, is along the bottom of the weld. It varies somewhat in thickness; above the poorly welded part is gray or crystalline material which had evidently been melted. To determine the strength of welds, from which this defect is removed, specimens No. 7, 10, 13, and 16 were grooved with a half round file along the bottom of the weld, as shown in B-3. The fractures for these showed no poorly welded band. The specimens showed a rather spongy dull gray surface with a large number of dark spots. An exception to this was specimen No. 15, which was almost entirely crystalline with no dark spots.

See Table 5 for general data for strip AH. As nearly as could be determined, the interruptions to the work occurred at specimens No. 11 and 14. These were noticeably low in strength. The specimens grooved to remove imperfect welding, No. 7, 10, 13, and 16, on the other hand, showed remarkable strength compared with the others. The high values for No. 10 and 13 may be due more to this fact than to the preheating. Evidently, this poorly welded portion of the specimens has been an important factor in causing low efficiencies, especially in these thin plates which had generally been left about $\frac{1}{32}$ in. thick at the beveled edge to prevent the blowpipe readily melting through the bottom of the groove. It is peculiar that specimen No. 15, welded without preheating, showed a good crystalline fracture while all preheated specimens had poor ones.

The average efficiency was 69.5%, the highest 88.0 % and the lowest 56.5%.

48. *Strip AJ.*—This strip was welded before the results for the previous one were available, so no precautions were taken to avoid poor welding at the bottom of the groove. The weld was built up, perhaps $\frac{1}{16}$ in., above the plate surface, as shown in B-1, Fig. 15, (p.38). After cutting the specimens, a 3-in. gauge length was laid off and prick-punched, having the weld in the middle. These specimens were then heated in a forge and drawn down on an anvil to a uniform cross section with a hand hammer. Two heats were required for this usually. The specimens were allowed to cool slowly. They showed an average elongation (see B-2) in the 3 in., due to forging, of 0.086 in. The greatest was 0.11 in. and the least 0.07 in. The surfaces of the weld were then ground smooth.

When tested, the poorly welded portion at the bottom, shown at B-1, appeared to have been drawn out in forging, (see B-2), causing a fracture similar to that shown at B-4. Specimens No. 12, 13, and 17, broke in this way, about half the thickness of the last being unwelded.

The first three specimens showed rather poor fractures but the remainder were better. There were no dark spots. Specimen No. 15 showed remarkable ductility in the material actually in the weld, B-5, and a good fine grained fracture. The same indications of ductility were shown in a lower degree by other specimens also. The average per cent elongation, 12.5, was high compared with previous welded specimens which average about 3 % in 6 inches.

See Table 5 for data. While the results are somewhat erratic, forging is evidently of value in increasing the ductility as well as the strength.

The average efficiency was 85.4%, the highest 124.6 % and the lowest 54.1%.

49. *Strip AI.*—To allow the poorly welded portion at the bottom of the weld to be ground away, leaving in the test weld only material which had been thoroughly fused, the plate edges, C-1, Fig. 15, were bent downward from $\frac{1}{32}$ in. to $\frac{1}{16}$ in., as in C-2, by hammering over the edge of an anvil. The weld when completed was much like C-3, and was then ground about as shown by the horizontal dotted lines.

The fracture showed very few dark spots on a gray surface and no poorly welded portion. Specimens No. 11, 12, and 15, showed a crystalline surface.

See Table 5 for data. The strength of this strip showed quite conclusively that lack of thorough welding was largely responsible for previous poor results.

The average efficiency was 86.6 %, the highest 104.6 % and the lowest 65.2%.

50. *Strip AK.*—To determine the effect of improper flame regulation this strip was welded with an excess of oxygen. The blowpipe flame was shortened by reducing the amount of acetylene until about half its length when properly regulated. This caused frequent "back firing", as the short flame made it necessary to work with the blowpipe close to the metal.

The method of working was the same as for strip AI, including thickening the weld by bending down the beveled plate edges. The fractures were much like those for the preceding strip. See Table 5 for data.

The average efficiency was 84.7 %, the highest 100.5 % and the lowest 72.5 %.

51. *Strip AL.*—This strip was welded in the same way as the last, including the thickened weld, except that an excess of acetylene was supplied. The second cone was, as nearly as could be estimated, 50 % longer than the first cone. As the second cone had a very fine point, its exact length was hard to determine.

The fractures were much like those for the preceding strip. See Table 5 for data.

The average efficiency was 83.1 %, the highest 92.0 % and the lowest 72.1%.

TABLE 5.

RESULTS OF STRENGTH TESTS OF WELDS —SECOND SERIES.

Strip	Efficiency per cent			Rate of Welding ft. per hr.
	Av.	Max.	Min.	
AB	72.1	77.9	62.5	1.32
AC	69.1	82.0	54.4	0.75
AD	78.2	94.8	72.0	1.55
AE	75.6	90.0	59.9	1.75
AF	72.0	87.4	44.8	1.51
AG	64.4	76.8	50.9	1.39
AH	69.5	88.0	56.5	0.92
AJ	85.4	124.6	54.1	1.17
AI	86.6	104.6	65.2	1.03
AK	84.7	100.5	72.5	0.90
AL	83.1	92.0	72.1	1.44

52. *Properties of Steel Plates.*—The unwelded specimens from these plates had sheared edges. Table 6 shows the average strength of specimen with sheared edges and with machined edges. The following method was used to compute the ultimate strength of a machined edge specimen from one having sheared edges. Two of the four specimens, for a number of the sections, were machined on the edges.

TABLE 6.

PROPERTIES OF STEEL PLATE—SECOND SERIES

	Sheared Specimen	Machined Specimen
Average ultimate stress, lb. per sq. in..	53 100	56 400
Range of variation from the average, per cent,	11.3	6
Average width, inches,	1.619	1.313
Average elongation in 6 in., per cent,	9	18

A study of Table 6 shows that, if the width of a sheared specimen is reduced 40% of the thickness of the plate for each sheared edge and this width used in computing the ultimate stress, it will agree closely with the average for a specimen having machined edges.

The same result may be obtained if the widths of specimens are nearly uniform as in this work by increasing the stress by a proper percentage; in this case six per cent. While this approximation saved much time in preparing specimens it is not to be recommended for work requiring a high degree of accuracy. In this case, however, it is believed that the data, upon which the correction is based, are taken from enough specimens to be reliable.

53. *Slope of Plates.*—During the process of welding all strips were sloped upward in the direction of welding about 1 inch in 7.7 inches. The greatest slope was 1 in 5, and the least 1 in 19. The exact amount is a matter of little consequence and will depend upon the preference of the operator and the conditions under which the work is done.

54. *Creep of Plates.*—The allowance for creep averaged 0.5 in. which was 2.56 % of the length of the weld. Two strips were welded satisfactorily with an allowance of $\frac{7}{16}$ in. and two with $\frac{9}{16}$

in. An attempt to weld a strip (AC) with only $\frac{3}{8}$ in. caused overlapping of the plates.

55. *Rate of Welding.*—The average rate of welding, 1.24 ft. per hr., for this series, seems very low when compared with the catalog value of 15 ft. per hr. Fig 16 shows the rates for all strips. The very low value of strip AC was due, doubtless, to the overlapping of the plates. Hammering the weld for strip AG and delays in working the torch when preheating strip AH lowered the rate for both these strips. The very short flame and frequent "back firing" also noticeably lowered the rate for strip AK, but there is no apparent reason why the remaining values should not be higher. Possibly the operator did not extend the weld as fast as circumstances permitted. If the only result was the low welding rate, it is of small consequence, but possibly the prolonged action of the blowpipe upon the metal was detrimental, causing lower efficiencies than would be found with a higher welding rate. The lower rates for the thickened welds, AI, AK, and AL, were doubtless due to the greater amount of filler to be added and the radiation from the greater mass of metal. Even for the first sections, the size larger blowpipe, No. 6, might have produced better results.

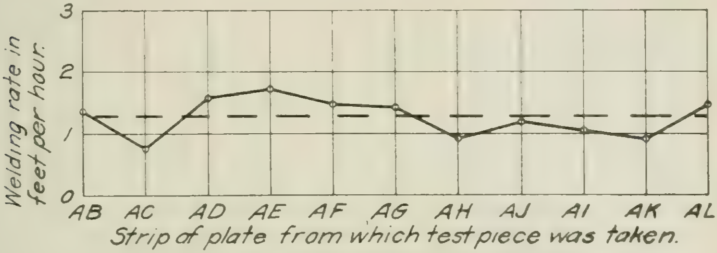


FIG. 16. RATE OF WELDING—SECOND SERIES.

56. *Hammering, Preheating, and Forging.*—While the results are far from conclusive, they tend to show that hammering the weld during the blowpipe operation is laborious and detrimental rather then beneficial.

Preheating undoubtedly increased the welding rate and so lowers the cost, but in so far as these results show, has little effect on the strength of the weld.

Forging produced a decided increase in the strength of the welds and also in the ductility of the fused metal. Apparently the increase in efficiency is about 10 %.

The average efficiencies and also the range of efficiency is shown in Fig. 17. Minimum efficiencies are shown both for end specimens and for inside specimens.

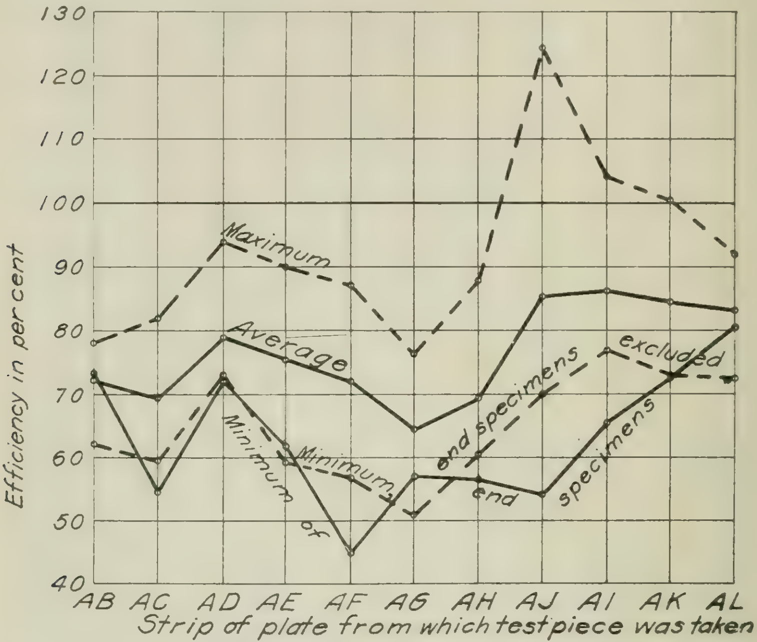


FIG. 17. EFFICIENCY OF WELDS —SECOND SERIES

57. *Effect of Thorough Fusion.*—The most important results of this series are obtained from the last three strips in which thorough fusion took place throughout the test weld. The average efficiencies were the highest obtained in these tests. The high average efficiency for strip AI, 86.6 %, confirmed as it is by the values for strips AK and AL, may be expected to be fairly representative of welds in $\frac{1}{8}$-in. steel when fusion has occurred throughout the weld.

58. *Effect of Flame Regulation.*—The variation of efficiency with the flame regulation is seen in Fig. 18. If it is remembered that the excess oxygen flame was difficult to manipulate, and that the second cone of excess acetylene flame was very conspicuous, it seems fair to assume that an ordinarily skillful workman would in practice have only about half the variations, either way, shown

here. If this were true, his blowpipe flame regulation would always lie between that shown in Fig. 4 (b) and that in Fig. 4 (d) with very slight corresponding variation in the efficiency of the welds.

The decrease in efficiency due to the excess oxygen flame was only 1.9 % and for the excess acetylene flame 3.5 %. There seems to be no excuse for a greater variation in commercial work due to improper regulation.

For comparison the results for strip D of the first series are given also in Fig. 18. When it is remembered that thorough fusion did not take place throughout this weld, the slight rise in efficiency for the excess oxygen flame is not surprising. Upon the whole the results for strip D confirm the results found for the second series very well.

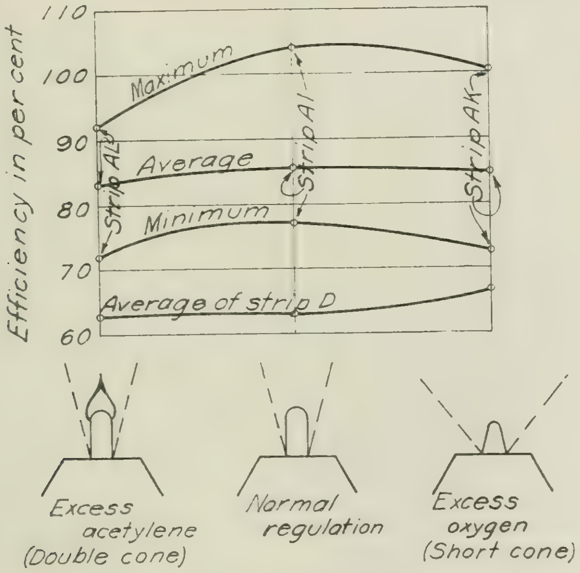


FIG. 18. EFFECT OF VARIATION OF FLAME REGULATION ON EFFICIENCY OF WELDS.

It would seem that a considerable variation from the normal flame regulation may be allowed without danger of greatly reducing the efficiency of the weld.

IV. Tests of Gases and Flame Regulation.

59. *Sampling Gases.*—As varying the flame regulation seemed to have little effect upon the welds in the second series, interest was renewed in the proportion of acetylene in the discharged gas and the variation in this amount for visible changes in the flame. Apparently the only way to determine the proportion of acetylene was to light the blowpipe and secure the desired regulation, then, after extinguishing the flame, to collect a sample of the discharged gases and make a chemical analysis.

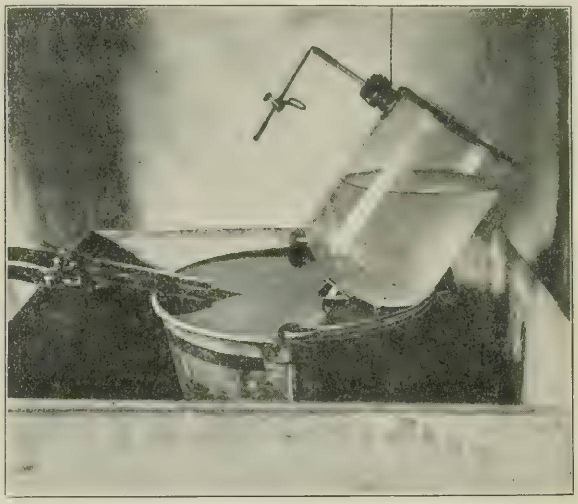


Fig. 19. Apparatus for Sampling Gases.

The apparatus for collecting samples of gas is shown in Fig. 19. A bottle was suspended by a slip noose at a fixed height for all samples. With the bottle placed mouth downward full of water and with the mouth of the bottle submerged under the surface of water in a pail, the blowpipe was thrust into the neck of the bottle and the discharged gas collected. This arrangement maintained atmospheric pressure upon the blowpipe tip so that the rates and proportions of the gases were the same as for the flame. Care was taken to keep the blowpipe tip on a level with the water outside the bottle. Probably the greatest variation from the proper level was a quarter inch, or possibly half an inch. The edge of the pail acted as a weir to maintain a constant water level outside the bottle. The time required to fill the bottle was observed. As the time was taken with an ordinary watch the greatest error may have been a second or two.

60. *Flame Regulation.*—For the first twelve gas samples taken the flame was extinguished by closing the tip for an instant, but back firing sometimes resulted, rendering the sample worthless. For all subsequent samples the acetylene cock on the hydraulic back pressure valve was closed to extinguish the flame, then reopened and the gas sample taken. By this method the positions of the cocks on the blowpipe, used in regulating the flame, were unchanged. After obtaining the sample the blowpipe was again lighted to prove that the regulation had not altered.

Three characteristic flame appearances were selected for this work, similar to those previously used (see p.13). In using the oxacetylene blowpipe the best results are usually obtained with a flame showing a single cone of the largest size possible. This regulation is termed "O K" or normal regulation. For this regulation slight variations in appearance were purposely introduced to determine their effect. Any sample of gas obtained with "O K" regulation showed a flame like that in Fig. 4 (c), or in some cases with a cone slightly shorter than that shown in Fig. 4 (c). So far as the results of the analyses show, the slight shortening of the cone was entirely inappreciable with the experimental errors which occurred in this work.

The regulation in which the length of the flame was 50% longer than when properly regulated is here termed the double-cone regulation, and is shown in Fig. 4 (b) fairly accurately. This regulation was used to determine the effect of excess-acetylene flame. For any flame there is some difference between its appearance in a photograph and when seen directly. It also makes considerable difference whether or not blue goggles are used. Although the outer cone flickered considerably at times, care was always taken to obtain as nearly as possible the appearance shown.

The excess-oxygen regulation obtained by reducing the amount of acetylene until the length of the first cone was one-half to two-thirds that when normally regulated, as is shown in Fig. 4 (d), was used to determine the effect of an excess of oxygen. Usually half-length of cone was obtained only with difficulty due to frequent "back fires". This regulation is termed short-cone regulation. Generally a scale placed parallel and close to the flame was used to assist in regulation.

For all these regulations, the oxygen cock on the blowpipe was full-open and the desired flame appearance was secured by adjusting the acetylene cock. In a few cases this latter was also full-open.

61. *Chemical Analysis of Gases.*—No attempt was made to determine the impurities in either oxygen or acetylene, simply the proportion of each with reasonable accuracy. The apparatus used is shown in Fig. 20. The gas sample was in bottle A, from which a measured volume was transferred to the graduated tube B. The acetylene in the mixture was absorbed by fuming sulphuric acid in C, and the remaining acid fumes by caustic potash in D. The volume remaining in the tube was then noted. This consisted of oxygen and the impurities contained in both the oxygen and acetylene.

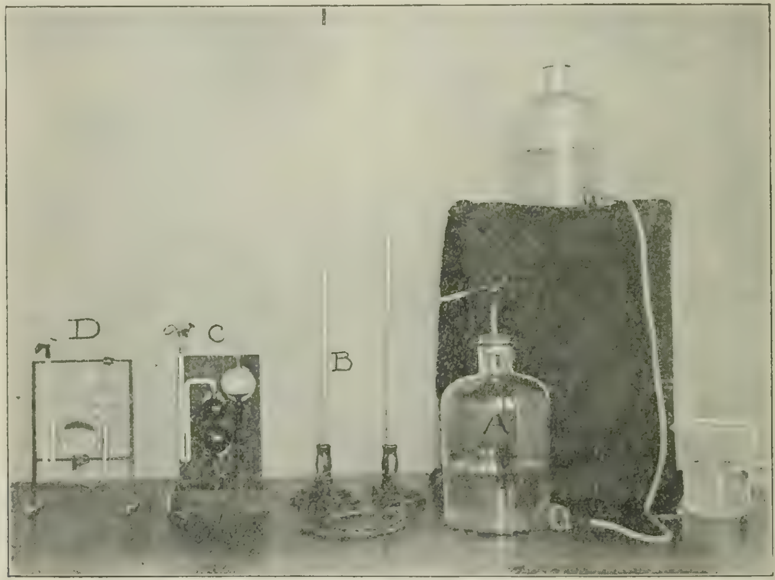


FIG. 20. APPARATUS FOR THE ANALYSIS OF GASES.

The data for representative samples are given in Table 7, which is largely self-explanatory. The volume of acetylene was, obviously, the difference between the initial and final volumes; but

TABLE 7.

SAMPLE GAS ANALYSES FOR OXYACETYLENE BLOWPIPE.

Sample No.	Blowpipe No.	Flame Regulation	Pressure of Acetylene in inches of water	Oxygen Pressure lb. per sq. in.	Initial Volume, cc	Final Volume, cc	Acetylene Volume, cc (A)	Oxygen Volume, cc (O)	Corrected Volume, cc (T)	Per cent Acetylene $(\frac{A}{T})$	Per cent Oxygen $(\frac{O}{T})$	Ratio of Oxygen to Acetylene	Bottle filled in seconds	Gas Rate, cu. ft. per hr.	Acetylene Rate, cu. ft. per hr.	Oxygen Rate, cu. ft. per hr.
1	5	OK	12	12	100.0 100.0	57.85 57.4	42.15 42.6	56.0 55.8	98.15 98.2	42.9 43.4	57.1 56.6	1.33 1.31				
									Av.	43.2	56.8	1.32				
2	5	OK	13⅜	0	99.9 99.7 98.3	1.1 1.3 1.0	98.8 98.4 97.3			99.0 98.6 99.0			100	5.34	5.31	
3	5	OK	13¾	0	86.1 95.8	2.0 2.4	84.1 93.1			97.5			100	5.87	5.87	
4	5	F	13¼	12	96.0 91.5 92.2 93.3	44.7 43.4 43.7 45.0	51.3 48.1 48.5 48.3	43.4 42.0 42.4 43.6	94.7 90.1 90.9 91.9	54.1 53.4 53.4 52.5	45.9 46.6 46.6 47.5	.846 .873 .875 .905	35	16.8	8.96	7.83
									Av.	53.4	46.6	0.875				
5	5	D	13⅜	12	92.1 90.1 93.0 89.4 96.1	50.8 50.3 52.5 58.1 62.7	41.3 39.8 40.5 31.3 33.4	49.3 48.7 51.0 56.1 60.9	90.6 88.5 91.5 87.7 94.3	45.5 45.0 44.3 35.7* 35.4*	54.5 55.0 55.7 64.3* 64.6*	1.19 1.22 1.26 1.80* 1.82*	43	13.65	6.14	7.51
									Av.	45.0	55.0	1.22				

F, Both acetylene and oxygen cocks full open.
D, Double-cone regulation.
*, Results omitted from average.

the oxygen volume was not so easily obtained. To make the results as accurate as possible, the impurities of both the gases were estimated and proper allowance made for them. The oxygen is guaranteed to be 95% pure and Dr. Jesse found by analyzing samples from a number of cylinders, none of which, however, was used for this work, that the highest per cent of oxygen was 98 and the lowest 96. It was, therefore, assumed that this oxygen was 97% pure. The first fifteen samples were from one oxygen tank and the remainder from another.

The acetylene manufacturers claim absolute purity for their gas. Attempts to analyze acetylene samples showed 99% for the first and a lower value for the second. Difficulty was found in manipulating the gas, due to the almost complete absorption, so that they seem to show only that the impurities could not exceed one per cent. Due to the lack of other definite information the statement of the manufacturers was accepted and the assumption made that the entire final volume was from the oxygen tank, 97% of which was oxygen. The sum of the acetylene and oxygen volumes gave the corrected volume upon which to base the oxygen and acetylene percentages as indicated in the column headings.

62. *Gas Consumption.*—The time required to fill the bottle varied from 110 to 15 seconds. If there was a possible error of 2 seconds in these readings the resulting gas rates would be in error 1.8 and 13.3%, respectively. Due to this fact, the oxygen impurities were ignored and the total gas rate apportioned between the oxygen and acetylene by the average percentage of each for the sample.

To determine the volume of gas collected, the bottle was weighed when full of water and again when bubbles escaped from the mouth. This was done by closing the mouth with the palm of the hand and weighing after removing the bottle from the pail. The gross weight was 6380 grams and the tare 1759 grams, making a net weight of 4621 grams. Neglecting temperature changes, this numerical value also measured the gas volume in cubic centimeters. The rate in cubic centimeters per second was then multiplied by the reduction factor 0.127 to obtain the gas rate in cubic feet per hour.

63. *Regulation Curves.*—The percentage of acetylene was chosen to measure the flame regulation, because it was the acetylene which was varied directly, although the ratio of oxygen to

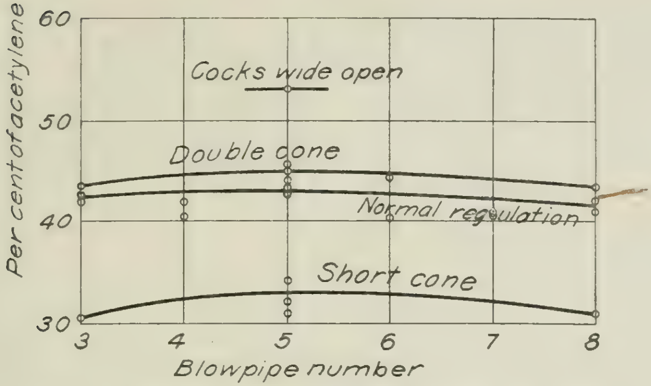


FIG. 21. EFFECT OF FLAME REGULATION ON THE COMPOSITION OF GASES.

acetylene might as well have been used. The average percentage for each sample is plotted in Fig. 21.

64. *Gas Consumption Curves.*—In a similar manner, the values for total gas consumption, or rate, and for acetylene were plotted in Fig. 22. In Fig. 22 are also plotted the rates given by the manufacturers of the blowpipe in their catalog.

65. *Oxygen Pressure and Regulation.*— For the previous graphs values are plotted only for samples taken with normal

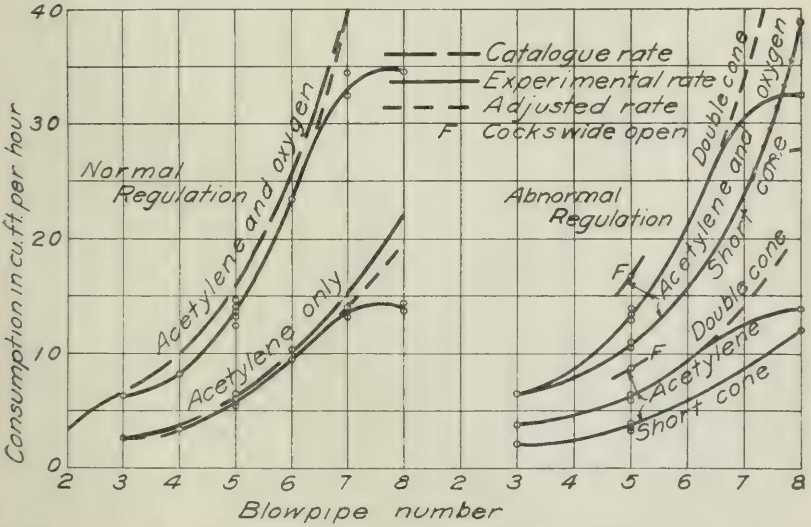


FIG. 22. GAS COMPOSITION WITH BLOWPIPES OF DIFFERENT SIZES.

oxygen pressure on the blowpipe. These pressures were as follows:

Blowpipe Number	Oxygen Pressure lb. per sq. in.
3	10
4	11
5	12
6	14
7	16
8	19

The only exceptions were for blowpipes 7 and 8 for which normal regulation could not be obtained, as is explained later. The acetylene was supplied under a practically constant pressure of about one foot of water for all series.

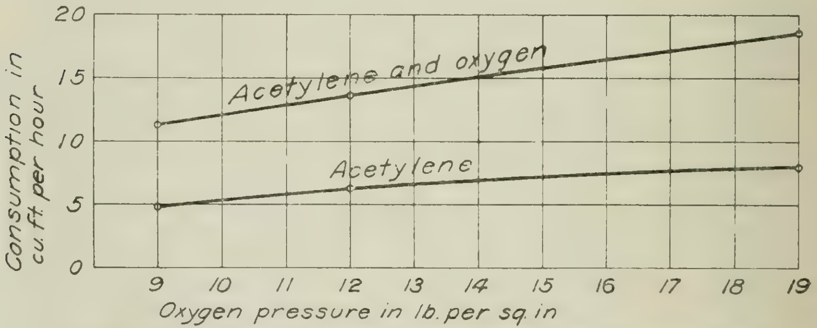


FIG. 23. EFFECT OF OXYGEN PRESSURE ON GAS CONSUMPTION.

The effect of varying the oxygen pressure upon the regulation and gas rates is shown in Fig. 23. Blowpipe 5 was used and normal regulation carefully maintained in each case. The values for the normal pressure (12 lb. per sq. in.) were those previously used.

The maximum and minimum pressures were fixed by the facts that trial proved that the flame "blew out" or was extinguished if the pressure was raised to 24 lb. per sq. in., making 19 lb. per sq. in. about the highest which gave a satisfactory flame and that the pressure gauge used did not read below 9 lb.

66. *Cost of Welding.*—The data given in the manufacturer's catalog for gas consumption for different blowpipes do not differ greatly from the data obtained in the tests herein described. It would seem then that the catalog data may be utilized to give the

cost of welds sufficiently accurately to allow comparisons to be made. Fig. 24 has been made up from these data. The cost of acetylene was taken as 1 cent per cu. ft.; of oxygen as 3 cents per cu. ft.; and of labor as 30 cents per hour. The curves need little explanation. The costs as shown by Fig. 24 are probably rather high, and lower costs may be obtained in practice. This applies in general to both the labor and gas items.

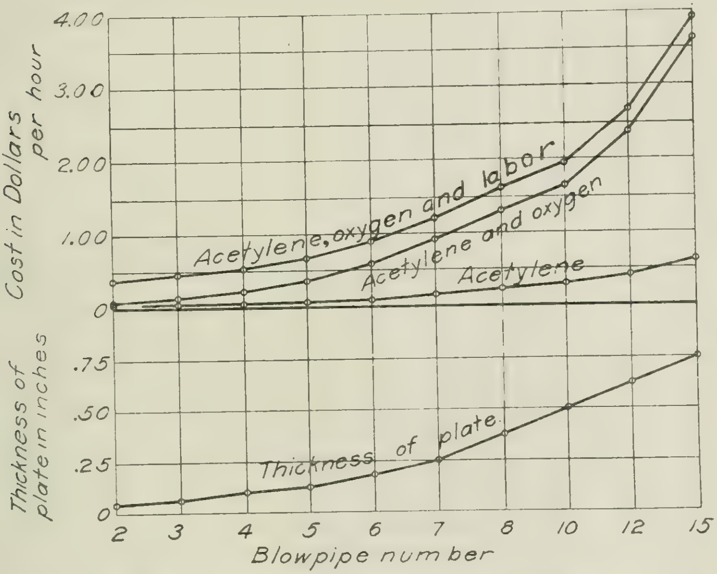


FIG. 24. COST OF OPERATION OF BLOWPIPES OF DIFFERENT SIZES.

67. *Discussion of Results.—Flame Regulation.*—The most striking feature of this work is the remarkable characteristic appearance of the blowpipe flame and its sensitiveness in showing changes in regulation. It seems safe to conclude that a change in the amount of acetylene of one per cent of the gas volume could be detected by the change in the appearance of the flame, provided, of course, that this occurred at or near the normal regulation. The flame is much more sensitive, also, in indicating excess acetylene than excess oxygen, so that a slight feathery flame tip is preferable to a slight or incipient shortening. All sizes of blowpipe appear to have practically the same regulation curve.

The proportion of acetylene for all sizes of blowpipes at normal regulation averages 42% in the tests. This is a ratio of 1.28 volumes of oxygen to one of acetylene, which is much less than the ratio 1.7 usually given. The ratio computed from the catalog rates for blowpipes 2 to 8, inclusive, is 1.61 to 1. The ratio of oxygen to acetylene does not seem to correspond to any definite stage in the oxidation of the acetylene gas. It does, however, appear to be a definite property of oxyacetylene blowpipe flames. As the gases are mixed before issuing from the blowpipe tip, it would appear to be a property entirely independent of the particular style or make of blowpipe. It may be noted that one manufacturer states that for their blowpipe the ratio of 1.28 oxygen to 1 of acetylene has been "adopted". Also that this is nearly the ratio fixed by the Academy of Science, France, which selected 1.30 to 1. The latter two values are nearer to those found by the tests than that given by the manufacturers and may be more nearly correct, but it would be interesting to know how the ratios were established. It would also be of interest to know whether a blowpipe can be designed which will show normal regulation for any ratio which may be selected at random.

Although experiments upon effect of flame regulation on the strength of welds in the first and second series did show a slight deterioration for improper regulation, the results tend to show that the effect must ordinarily be very slight. With a change in the amount of acetylene of perhaps only 2 or 3%, at most, of the total gas volume, it is difficult to believe that much difference in the chemical composition of the materials in the weld can result, especially when the short time that the flame is in contact with any particular portion of the material is considered.

68. *Gas Consumption.*—As was to be expected, the gas rate increased with the size of the blowpipe. The experimental rates are very nearly those given in the catalog of the manufacturers of the blowpipe, particularly for the acetylene. As the ratio of acetylene to oxygen, from the catalog, differs considerably from that found from analyses, it is impossible for both the oxygen and acetylene rates to check very closely with those in the catalog.

The gas rates for blowpipes No. 7 and 8 with double cone regulation appear low, and should follow the dotted lines in Fig. 22. It was noticed when gas samples for these were taken that no second cone appeared with both oxygen and acetylene cocks full-open. There was, therefore, an insufficient supply of acetylene for normal regulation with normal oxygen pressure. The oxygen pressure was therefore reduced to produce normal regulation. This accounts for the low gas rate. The blowpipe body was intended for use only with heads up to and including No. 7, but the No. 8 head was supplied for this work by request. Evidently the acetylene passages, in the body, are barely large enough for the No. 7 head and totally inadequate for the No. 8. Increasing the acetylene pressure might overcome this difficulty. In all the gas consumption curves, therefore, the portion for blowpipes 7 and 8 should be considered abnormal, due to a varying oxygen pressure. The regulation curves show, however, how persistent is the flame's characteristic appearance for these abnormal conditions.

69. *Oxygen Consumption.*—Due to the low pressure of the acetylene, about 0.4 lb. per sq. in. (12 in. of water) and the high oxygen pressure (12 lb. per sq. in. for blowpipe No. 5), it appears probable that the oxygen rate remained constant, or nearly so, for all flame regulations. If any change occurred, it would be a decrease in the oxygen rate as the acetylene rate increased. Omitting abnormal samples, the averages of the oxygen rates for blowpipe 5 are as follows: Both cocks full-open, 7.83; double-cone regulation, 7.48; normal regulation, 7.69; short-cone regulation, 7.53; average, 7.63 cu. ft. per hr. The variations from this average are just the opposite from those expected. The variations range from 2.6% above to 2.0% below the average, and might be caused by an error of one second in the time reading. This leads to the conclusion that the oxygen rate is practically constant for any given blowpipe and oxygen pressure, and is independent of the acetylene rate. This would have been more apparent in the graphs if the oxygen rate had been plotted below the acetylene rate.

The strikingly high gas rate for blowpipe No. 8, for short cone regulation, shown in Fig. 22, is explained by the high oxygen pressure used. If it is assumed that the rate is proportional to the square root of the pressure, the curve for short-cone regulation acetylene and oxygen in Fig. 22 may be corrected approximately as shown by the dotted line.

The increase of oxygen rate with increase of pressure is very noticeable in Fig. 23, and there is a nearly proportional increase in the acetylene rate. Although this increase is not exactly proportional to the square root of the pressures, the difference appears to be less than the experimental error.

70. *Cost of Operation.*—The great increase in the cost of operation as the size of blowpipe increases may be seen from Fig. 24, as well as the small proportion of the cost represented by labor even at the high rate of pay assumed. This indicates that oxyacetylene blowpipes are best adapted, commercially, to plates up to about $\frac{1}{2}$ in. in thickness.

The fact that the welding rate, based on the cross sectional area of weld, is very nearly constant at 17.5 sq. in. per hr. is seen in Fig. 25. This is the value used in estimating the probable welding rate on any given thickness of plate.

The cost of welding plates of any given thickness may be estimated also at 25 cents per cubic inch of filler used. This is, of course, subject to the assumed costs and would be proportionally altered for other values. This cost holds, however, only for plates over $\frac{1}{8}$ in. in thickness and must be doubled for $\frac{3}{64}$ in. plates. It should also be noticed that, provided this rate holds for any type of grooved joint, if the plates were grooved from both sides, as shown at (c), Fig. 8, the cost per foot of weld would be only half that for plates grooved from one side only, as shown at (b), because the required amount of filler would be reduced one-half.

71. *Summary for Tests of Gases.*—The appearance of the blowpipe flame is a very sensitive indicator of changes in the proportions of oxygen and acetylene when near normal regulation.

The average proportion of acetylene at normal regulation is 42.0%, a ratio of 1.38 volumes of oxygen to 1 of acetylene.

The oxygen consumption is practically constant for any given size of blowpipe and oxygen pressure and independent of the acetylene rate.

Apparently the oxygen rate is proportional to the square root of the oxygen pressure.

The percentage of acetylene is very nearly constant for normal regulation with any oxygen pressure.

The minimum oxygen pressure is reached when the flame "back fires" so frequently that satisfactory work is impossible.

The maximum oxygen pressure is reached when the flame "blows out" or is extinguished by the high velocity of the gases.

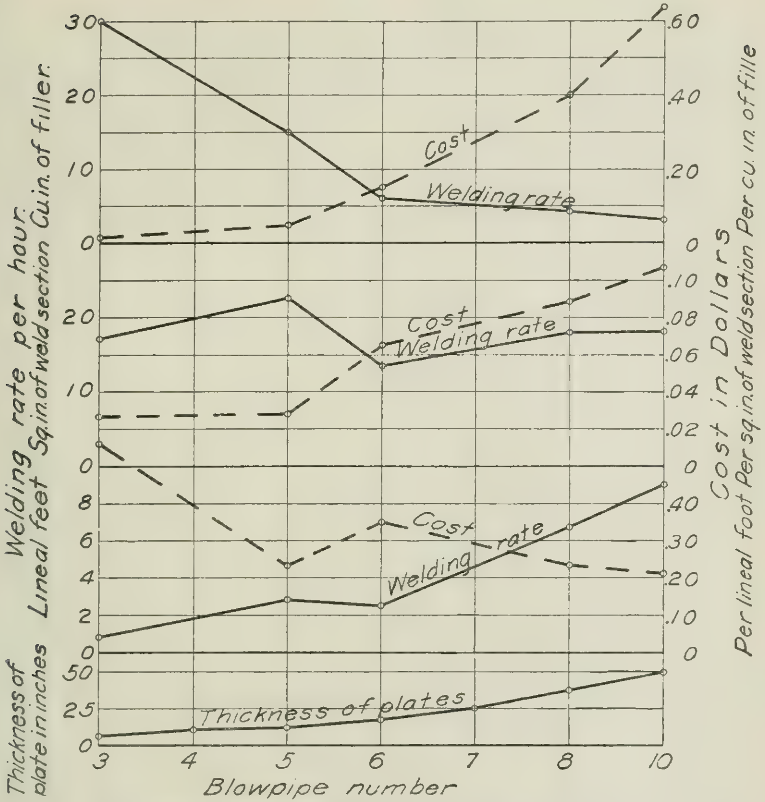


FIG. 25. WELDING RATE AND COST IN TERMS OF LENGTH OF WELD, SECTION OF PLATE, AND VOLUME OF FILLER FOR BLOWPIPES OF VARIOUS SIZES.

Normal regulation is impossible at the maximum oxygen pressure and is obtained only at some lower pressure.

The cost of operation for oxyacetylene blowpipes rises very rapidly as the thickness of plate is increased, reaching, possibly, four dollars an hour for the gas and labor for work on plates of three-quarter inch thickness.

The welding rate is nearly constant at 17.5 sq. in. of weld section per hour.

The cost of welding beveled plates is about 25 cents per cubic inch of filler, assuming oxygen at three cents per cubic foot, and acetylene at one cent per cubic foot, and labor at 30 cents per hour.

V. General Conclusions.

72. *Heat Treatment.*—The meager amount of information obtained regarding the effect of heat treatment and subsequent working of the welded material leaves an important and probably very fertile field still to be covered. The rather remarkable results obtained by forging after welding appear to be in agreement with the known properties of metals. Highly heated steel, upon cooling, has a coarse crystalline fracture and low tensile strength. This condition can be improved by reheating to the lowest temperature which will produce a fine grain and then cooling. In this way, the finest grain and also the highest tensile strength will be obtained. Steel heated to, or near, fusion is "burnt" and greatly damaged. The injurious effects of "burning" of steel appear to be due, in part at least, to the "oxidation of the faces of the crystalline grains which compose the metal, by inward diffusion of the atmospheric oxygen" (Howe). The oxyacetylene blowpipe flame, if properly regulated, is a reducing flame as is shown by the reduction of the surface film of oxide of the filler wire, and the injurious oxidizing effect may be small in metal welded by an oxyacetylene flame. "Burnt" metal can never be completely restored to its original condition. While annealing alone will restore steel if merely overheated, steel which is "burnt" requires mechanical working, such as hammering or rolling while hot to cause much improvement. For a discussion of the cause of and remedies for "burnt" steel see Howe's "Iron, Steel and Other Alloys," pp. 241—276.

It seems probable that the coarse crystalline fractures and low efficiencies found for these oxyacetylene welds are produced necessarily by the very nature of this or any other welding process which requires fusion of the material. It is even possible, then, that blowpipe welding may prove superior to other methods involving the use of gas or coal, since the reducing action of the oxyacetylene flame may prevent the oxidizing of the crystals found in "burnt" steel. In any case, maximum efficiencies can be obtained only by using every available means to reduce the effects of overheating. This would require annealing and, if practicable, hammering or rolling.

It is often claimed that welds can be strengthened any required amount by adding filler to increase the thickness. This, however, is obviously only a partial remedy, as the material adjacent to that where filler is added is always overheated. When rupture occurs just outside the weld, due to this overheating, the weld can not be considered to be as strong as the rest of the material.

73. *Efficiency.*—Skill in the manipulation of the oxyacetylene blowpipe and in making welds may readily be acquired by the ordinary workman. As already stated, the appearance of the flame is a delicate indication of proper regulation. The principal precaution to be observed by the workman is to be sure that thorough fusion has taken place.

The data on consumption of gases, and on pressure and regulation given in IV. Tests of Gases and Flame Regulation may be applied to various conditions of operation. The cost of operation of a blowpipe rises very rapidly as the thickness of the plate to be welded increases, and this fact may limit the field of usefulness of the oxyacetylene blowpipe to the welding of thin plates and parts and to emergency repair jobs.

The efficiencies of welds obtained in the investigation are summarized rather fully in paragraphs 31 to 36, 53 to 58, and 67 to 71. A consideration of the results leads to the conclusion that thorough fusing of the material in the weld and forging of the finished weld were the only conditions which resulted in any noticeable increase in the efficiency of the welds. Forging after welding produced a decided increase in the strength of the welds and also in the ductility of the fused metal—apparently the increase in efficiency of the weld was about 10%. In the three strips in which thorough fusion took place throughout the weld, the average efficiency was the highest obtained in the tests. In view of the comparisons hitherto made, the efficiency found for one of these strips, 86.6 %, may be expected to be fairly representative of welds in $\frac{1}{8}$-in. steel when fusion has occurred throughout the weld.

The average technical article describing this process apparently lays too much emphasis upon the necessity for very careful flame regulation and for pure oxygen and acetylene, as well as on the value of preheating and hammering the weld as it is made, in securing high efficiency. A claim of 100% efficiency is insupportable. It appears that 85% is about as high as may be expected in practice if the weld is of the same thickness as the plate.

In spite of certain inherent defects the oxyacetylene process is well adapted to many welding operations, and it is likely to grow in favor as its advantages are understood.

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BULLETIN No. 46 DECEMBER 1910

THE SPONTANEOUS COMBUSTION OF COAL

WITH SPECIAL REFERENCE TO BITUMINOUS COALS OF THE ILLINOIS TYPE

BY S. W. PARR, PROFESSOR OF APPLIED CHEMISTRY AND
F. W. KRESSMANN, GRADUATE ASSISTANT IN
APPLIED CHEMISTRY

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THE SPONTANEOUS COMBUSTION OF COAL

WITH SPECIAL REFERENCE TO BITUMINOUS COALS OF THE ILLINOIS TYPE

I. Introduction

The coal production in Illinois, in 1907 and also in 1908, amounted, each year, to 51 million tons, valued at 52 million dollars. There was a slight increase in 1908 over the tremendous production in 1907, in spite of the labor troubles which caused a complete shut-down of mining, beginning with the April, 1908, conference of miners and operators. The general business depression of that year caused many consumers to use the cheaper grades of bituminous coals in preference to the more expensive anthracite, and, since production at the mines was thus stimulated before and after the shut-down, the public felt no shortage of fuel. Such a situation is unnecessarily expensive both for the consumer and the miner, as a uniform daily output is necessary in order to procure and maintain the most economical production of coal. However, having secured such a uniform daily output, it is manifest that a production of coal so great as that given above cannot be guaranteed to meet fluctuations in daily demand.

To guard against unknown and unforeseen conditions, such as labor difficulties, variations in output or delay in transportation, the large manufacturing interests are beginning to see the need of storing large amounts of reserve fuel. Variations, due to seasonable demands of fuel for domestic purposes, also necessitate the storage of coal either by the mining interests or by the coal dealers. In the maritime world, the storage of coal is one of the great problems of today. Our large battle ships and ocean greyhounds use upwards of 500 tons of coal per day, and hence coal must not only be stored on shipboard, but large reserve supplies must be on hand at the various coaling stations.

On the other hand, wherever large quantities of bituminous coal are stored,—and bituminous coal furnishes by far the greatest part of the energy used at the present day,—the danger arising from spontaneous combustion must be taken into consideration, and hence elaborate and costly measures are being taken to avert this hidden peril. The problem of spontaneous combustion is rapidly being recognized as the great problem in the storage of bituminous coals.

The United States government, which uses upwards of a quarter of a million tons of coal yearly for the navy alone, has taken great precautions to avert the danger of spontaneous combustion in its new coal pile at Bradford, on Narragansett Bay, near Newport, where the storage capacity is about 60 000 tons.

The coal bins or pockets are provided with temperature tubes, so that if incipient heating should occur it will be discovered and located long before a temperature has been reached at which combustion commences. These tubes consist of lengths of 4 in. galvanized pipe about 20 feet long, set in the bin floors and projecting upwards through the coal pile. They contain thermostats which are arranged to indicate temperatures in excess of 150°F. Circuits are run from the 232 tubes to a general annunciator in the superintendent's office, so that if heating does occur an alarm is at once sounded and the exact position of the pile where the heating has developed is shown on the indicator.

The temperature of 150°F. was decided upon as the danger point as the result of numerous experiments made by the Navy Department which indicated that if the temperature of the coal reached this point the increase in temperature beyond was very rapid.[1] At the New York Navy Yard, compartments of 525 gross tons capacity have been built. The floors of these bins are of portland cement, and the side walls are made of a mixture of portland cement, sand, and anthracite boiler cinders. The roofs are of iron[2].

The danger of spontaneous combustion on shipboard is even greater than during ordinary storage, for the coal is usually stored in whatever space is unoccupied by other materials, usually at the side of the vessel between the boiler rooms and the side planking. Here the coal is subjected to the heat of the boiler and engine rooms, and is especially liable to ignite spontaneously.

Up to the present time a great deal of excellent work together with a considerable amount of theorizing regarding the nature and cause of spontaneous combustion has been done, but the views presented have been very contradictory, as a study of the Appendix will reveal. It seemed probable, therefore, that the differences in the particular varieties of coal worked with might have been the cause of the various theories advanced, and that seeming truths and generalizations drawn from work on a specific coal are not applicable to coals in general.

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[1] Chemical Engineering, June 1906

[2] Engineering News, July 21, 1904, page 68

On assembling the results of many investigations in this field, it was found that the primary conditions which lead to spontaneous combustion are considered to be as follows:

(1) The presence of pyrite.
(2) The size of coal.
(3) The initial or induced temperature of the coal.
(4) The presence of moisture.

While these results are extremely suggestive, they cannot be looked upon as conclusive or necessarily applicable to the problems in this region connected with coal storage. Two reasons, at least, may be given in support of this statement. (1) Such an assembling of results gives no suggestion as to the relative importance of the various influences. (2) The conclusions of an investigator based upon experiments with one type of coal might not apply in the case of a coal differing in texture and chemical composition. These two features must be understood for any given type of coal before any safe statements can be made regarding that particular region. For example, while it may be true of any coal that the above enumerated causes are operative, it is more important in any case to know the order of their importance. Again, in the case of coals from the midcontinental fields, i. e., of the Illinois type, a peculiarity of the composition exists which may enter into the problem as a factor. The coals of this region, for example, are characterized by a high content of moisture seldom below 10 per cent and averaging 12 to 15 per cent at the vein. This is in marked contrast to coals of the same general type of the eastern United States and Europe, where this factor rarely exceeds 2 to 4 per cent. Again, this fact, while perhaps not so significant in itself is always accompanied by another item which may have some bearing in that this large water content is always accompanied by a higher content of oxygen combined as a part of the organic matter, in contrast with the lower oxygen content of the low moisture bituminous coals. Also, the high sulphur content of Illinois coal, ranging from 1 to 6 per cent, with the average at about 4 per cent, may materially influence the spontaneous combustion of this type of coal.

The Illinois bituminous coals, with their high moisture and ash, varying amounts of sulphur and inert volatile matter, seem, therefore, to require special study in order to establish the reasons for their property of spontaneous combustion. The subject naturally divides itself into three subdivisions: first, the determination, if possible, of the causes of spontaneous combustion; second, the relative importance of these causes; and third, the removal, if possible, of this property of spontaneous combustion either through the treatment of the coal by chemical processes or through certain methods of handling.

II. OUTLINE OF EXPERIMENTAL INVESTIGATIONS

GENERAL DESCRIPTION OF METHODS AND APPARATUS

Coal from Williamson county, Illinois, marketed under the trade name of "New Ohio," was used for these experiments. The composition of the various samples will be found on pages 9 and 14. About one-half ton of large lumps was required for the experiments. These lumps were ground to the requisite sizes. The grinding was done in a small Chipmunk crusher and the ground coal was then run through a revolving screen, by which it was sized. The screen used was of the revolving or trommel type, made of perforated steel plate about 6 ft. long and 1 ft. in diameter, in which holes of the following sizes were drilled: $\frac{1}{8}$ inch, $\frac{1}{4}$ inch, $\frac{3}{8}$ inch, $\frac{1}{2}$ inch, $\frac{3}{4}$ inch, 1 inch. The coal coming through the $\frac{1}{4}$ inch holes, known as size $\frac{1}{8}$-$\frac{1}{4}$ was always screened twice because a small amount of dust escaped the $\frac{1}{8}$-inch holes the first time; in order to make the $\frac{1}{8}$–$\frac{1}{4}$ size dust-free it was re-screened. Each time only enough coal was ground and screened to meet immediate demands and any left over was thrown away, so that the coal used was always fresh and unoxidized.

The most potent elements in the case were believed to be temperature, fineness of division, pyrites and the amount of moisture present. These are taken up in the order given.

1. *Effect of Temperature and Size.*—In studying the effect of external temperature the general principle was adopted of placing rather large, 25 to 35 lb., samples within an insulated space,

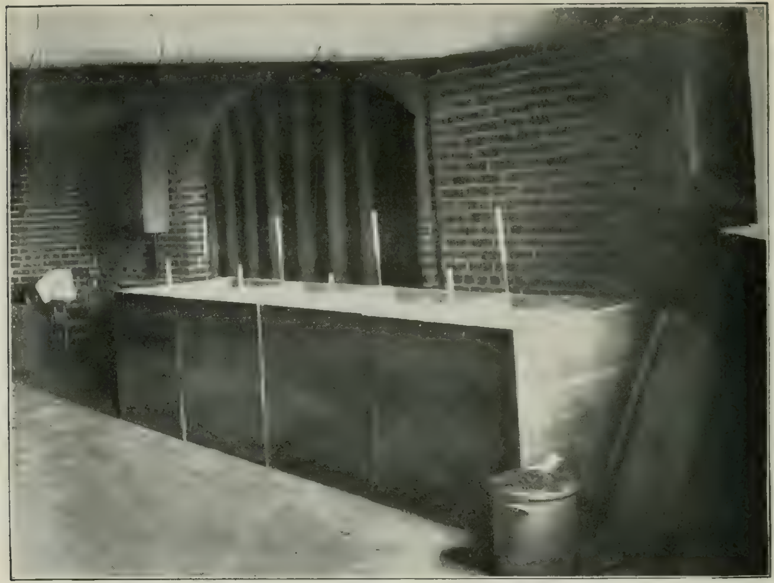

Fig. 1.
General View of the Ovens, Showing Thermometer Arrangement and a Sample Jar of Coal.

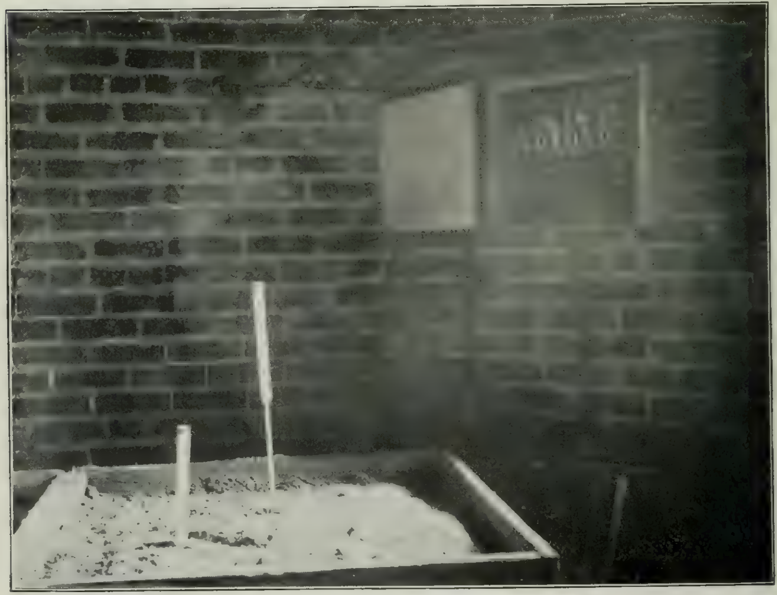

Fig. 2.
A View of the Temperature Regulating Apparatus and Detail of One of the Ovens.

where the atmosphere immediately surrounding the sample could be kept under exact control. By means, then, of thermometric readings taken within the coal mass and also from the atmosphere of the chamber, any oxidation within the coal sample would be indicated by a rise of temperature above that of the surrounding atmosphere. The details as to the time, temperature, construction and general procedure were as follows:

2. *Methods and Apparatus.*—The coals were placed in the constant temperature ovens for a period of three days each, as, in the preliminary experiments that were run, it was found that a period of 72 hours was sufficient to give the maximum rise in temperature. The following temperatures were maintained in four different ovens; 40°, 60°, 80°, 115° Centigrade. The coal was first placed in the 40° oven, and after a period of three days, it was moved to the 60° oven; after another period of three days, it was moved to the 80° oven; and finally, after another period of three days, it was moved to the 115° oven; after remaining in this oven for three days the coal was removed. A 5-gal. stone jar having the bottom perforated with ½-in. holes was used as a container for the coal. A jar of this size held a sample of coal weighing about 35 or 40 lb.

The ovens were constructed as follows. They consisted of two wooden boxes, one set inside the other. The boxes were in the form of cubes, the outer box being a 3-ft. cube made of 1⅛-in. pine boards; the inner box was also in the form of a cube, made of the same material only it was 8 in. smaller than the outside box. This left a space of 4-in. on all sides between the two boxes, and this space was tightly packed with mineral wool, the inner box being well insulated in this manner. Across one corner of the inner box a board was nailed. This board was 4 in. shorter than the box and was nailed into the box so as to leave a clear space of 2 in. at the top and bottom of the box. The triangular space formed by this board and the corner of the box was lined with ¼-in. asbestos board so as to insulate it. This space then formed a chimney, and near the bottom of this chimney the electric lights used to heat the boxes were hung. The temperature was regulated by means of a mercury regulator which consisted of a large bulb of mercury expanding up a capillary tube. A platinum wire was fused into the bulb so as to be in contact with the mercury. Down the top of the capillary tube a long, fine needle was placed so that when the mercury was expanded to a certain height at a definite temperature the mercury would just come in contact with the needle. Wires were run from the regulator to a telegraph relay, the mercury regulator being connected in series in this circuit. This outfit was run by storage battery current. The telegraph relay was used to make and break the 220-volt circuit on which the lights used for heating were connected.

The jars of coal were placed on several bricks in the inner box, the bricks being arranged so as to elevate the jar high enough so that it would be in the middle of the box, and also to allow the air around the jar to circulate freely. The cover of the inner box was then put into place, and through the holes in the latter several long thermometers (about 2½ ft. long) were placed to indicate the temperature of the air in the box and also the temperature of the coal. The thermometers used to indicate the temperature of the air in the box were placed so that one was near the heating chimney and the other was at a point farthest from it. The thermometer used to indicate the temperature of the coal was placed so that the bulb was 4 or 5 in. below the surface of the coal. Readings of these temperatures in degrees Centigrade were taken every morning and afternoon.

In the first run, called Series 1, five sizes of the coal were used. These samples were not what would be known as air-dry, because the coal was used as soon as it was ground; the large lumps, however, were air-dry. The five sizes were as follows:

Size 0: This size included some of the coal that went through the smallest holes in the screen and then was ground in a disk pulverizer until it was very finely divided. About 75 per cent of this size went through a 120-mesh screen, and all of it went through an 80-mesh.

Size 0–⅛: This coal went through the ⅛ in. holes in the large revolving screen.

Size ⅛–¼: This coal went through the ¼ in. holes in the screen.

Size ¼–⅜: This coal went through the ⅜ in. holes in the screen.

Size ⅜–¾: This size was a mixture of equal parts of the coal that went through the ½ in. and the ¾ in. holes in the revolving screen; it was thought that there would not be enough difference between the results of the ½ in. and the ¾ in. size, so the two were mixed in equal proportions.

DETAILS OF EXPERIMENTS

Experiments were conducted in 15 series. Each series represented experiments upon certain chosen sizes of coal, and all the coals of a given series were subjected to the same conditions. Each series differed from the others by one variable as to condition, such as dry or wet, varying content of pyrites, etc.

Composition of Coal. The composition of the coal used in the first five series, as indicated by a proximate analysis, was as follows:

TABLE 1

	Size 0–⅛ per cent	Size ⅛–¼ per cent
Moisture	4.16	4.62
Volatile Matter	33.48	33.37
Fixed Carbon	50.86	50.88
Ash	11.50	11.13
Total	100.00	100.00
Sulphur	1.26	1.29
Calculated to Dry Coal		
Volatile Matter	34.92	34.78
Fixed Carbon	53.08	53.58
Ash	12.00	11.64
Total	100.00	100.00
Sulphur	1.32	1.35

The pyritic iron was determined by taking the difference between the total iron in the coal and the iron soluble in dilute hydrochloric acid. The results for the above two samples are as follows:

	Size 0–⅛ per cent	Size ⅛–¼ per cent
Total iron	1.91	1.73
HCl soluble Fe	0.73	0.67
Pyritic iron	1.18	1.06
Calculated Pyrite content	1.76	1.60

Inasmuch as more of the larger sizes were used than the finer, the average pyrite content of the coal was taken as 1.65 per cent.

Series 1.—A jar of each of the four largest sizes of coal was placed in the ovens in the same increasing ratio of size of the coal and the temperature of the oven, e. g., size 0-$\frac{1}{8}$ was put in the 40° oven, size $\frac{1}{8}$-$\frac{1}{4}$ in the 60° oven, size $\frac{1}{4}$-$\frac{3}{8}$ in the 80° oven, and size $\frac{3}{8}$-$\frac{3}{4}$ in the 115° oven. This method of procedure was adopted to save time, for by this means all the ovens could be filled at once, and since it took 12 days for a coal to pass through the four ovens, a considerable saving of time resulted, and the large sizes of coal were not oxidized to an appreciable extent at these low temperatures. After the coals had remained in the ovens for three days, they were moved up to the next oven, size $\frac{3}{8}$-$\frac{3}{4}$ was taken out of the 115° oven and the next smaller size put in, and size 0 was put in the 40° oven. The reading of the temperatures was made in the morning and afternoon, chiefly to see that the regulators were working well and that the lights were not burned out, and also to get the increase in temperature of the coal over that of the ovens. As is shown in Table 2, the

TABLE 2

SERIES 1—DRY COAL—1.65 PER CENT PYRITE

	Coal 0	Coal 0-$\frac{1}{8}$	Coal $\frac{1}{8}$-$\frac{1}{4}$	Coal $\frac{1}{4}$-$\frac{3}{8}$	Coal $\frac{3}{8}$-$\frac{3}{4}$
Time in hours	96.0	89.0			
Oven temperature °C	38.8	40.0			
Coal temperature °C	41.7	42.5			
Rise temperature °C	2.9	2.5			
Time in hours	89.0	76.0	89.0		
Oven temperature °C	60.0	60.5	60.0		
Coal temperature °C	65.0	63.7	63.5		
Rise temperature °C	5.0	3.2	3.5		
Time in hours	77.0	74.0	76.0	89.0	
Oven temperature °C	80.0	80.0	79.8	77.0	
Coal temperature °C	95.0	91.1	89.7	78.0	
Rise temperature °C	15.0	11.1	9.9	1.0	
Time in hours	42.0				
Oven temperature °C	108.0				
Coal temperature °C	168.0				
Rise temperature °C	60.0				
Time in hours	72.0	89.0	74.0	76.0	89.0
Oven temperature °C	108.0	109.0	107.8	108.0	107.0
Coal temperature °C	154.0	140.0	133.2	127.9	122.4
Rise temperature °C	46.0	31.0	25.4	19.9	15.4

maximum rise in temperature in some cases took place before the end of three days. This was especially the case in the dry, finer sizes. The average temperature of the ovens and the temperature of the coal at the end of the three days are shown in Table 2.

Series 2. Series 2 was the same as Series 1, the only difference being that the coal in Series 2 was thoroughly wet before being placed in the ovens.

Before beginning Series 2, in order to get some idea as to the oxidation of the coal and the amount of oxygen used up by it, the air in the different ovens was analyzed, after the coal had been in the ovens for three days. The results were as follows:

	Oven 1—40°	Oven 2—60°	Oven 3—80°	Oven 4–115°
Per cent CO_2	0.40	1.20	1.00	1.81
Per cent Oxygen....	20.00	18.40	19.40	16.00

Since the oxygen content decreased so much, it was thought

TABLE 3

Series 2—Wet Coal—1.65 Per Cent Pyrite

	Coal 0	Coal 0–$\frac{1}{8}$	Coal $\frac{1}{8}$–$\frac{1}{4}$	Coal $\frac{1}{4}$–$\frac{3}{8}$	Coal $\frac{3}{8}$–$\frac{3}{4}$
Time in hours..................	72.0	81.0			
Oven temperature °C	38.5	38.5			
Coal temperature °C	38.3	38.5			
Rise temperature °C	....	....			
Time in hours	84.0	72.0	81.0		
Oven temperature °C............	60.0	59.0	59.5		
Coal temperature °C	57.5	58.5	62.4		
Rise temperature °C	....	....	2.9		
Time in hours............	72.0	84.0	72.0	81.0	
Oven temperature °C	80.0	80.0	80.0	80.0	
Coal temperature °C	86.5	85.5	86.3	85.6	
Rise temperature °C	6.5	5.5	6.3	5.6	
Time in hours	48.0				
Oven temperature °C	111.5				
Coal temperature °C	168.3				
Rise temperature °C	56.8				
Time in hours	72.0	72.0	84.0	72.0	81.0
Oven temperature °C	114.0	111.9	110.2	112.5	111.5
Coal temperature °C	164.8	148.2	131.0	128.0	125.5
Rise temperature °C	50.8	36.3	20.8	16.5	14.0

necessary to ventilate the ovens so as to maintain atmospheric conditions. This was done by boring several $\frac{1}{2}$-in. holes through the walls of both boxes near the bottom and putting a $\frac{1}{2}$-in. glass tube through the two walls. One of the tubes was placed so that the fresh cool air that came in was delivered at the bottom of the heating chimney, and the other tube delivered its air at the opposite side of the box. At the top of the box a take-off pipe of the same size was inserted.

Series 3.—In Series 3 and 4 the content of iron pyrites was increased over the amount in Series 1 and 2 so that the total of iron pyrites in the form of FeS_2 was 3 per cent. This was accomplished by taking some large lumps of pyrite just as it occurs in the coal measures of Vermilion County. This was ground to pass through a 20-mesh sieve, and upon analysis was found to be 87.62 per cent pure. This calculation of purity was based upon the sulphur content of the material, which was 46.73 per cent. In Series 3 the variable from Series 1 is in the content of pyrite which has been increased from 1.65 per cent to 3 per cent. Tests upon the two larger sizes were omitted for the reason indicated in Tables 2 and 3. The oxidation on these larger sizes was too small and not different in character from the reaction upon the finer sizes, hence they were omitted from the subsequent experiments.

TABLE 4

SERIES 3—DRY COAL—3 PER CENT PYRITE

	Coal 0	Coal 0–$\frac{1}{8}$	Coal $\frac{1}{8}$–$\frac{1}{4}$
Time in hours	71.0	71.0	
Oven temperature °C	37.0	39.5	
Coal temperature °C	42.0	42.0	
Rise temperature °C	5.0	2.5	
Time in hours	72.0	71.0	71.0
Oven temperature °C	60.0	60.0	66.0
Coal temperature °C	68.2	67.5	60.0
Rise temperature °C	8.2	7.5	6.0
Time in hours	72.0*	72.0	71.0
Oven temperature °C	75.0	80.0	81.5
Coal temperature °C	88.6	93.5	93.8
Rise temperature °C	13.6	13.5	12.3
Time in hours	30.0		
Oven temperature °C	115.0		
Coal temperature °C	190.3		
Rise temperature °C	75.3		
Time in hours	72.0	72.0*	72.0
Oven temperature °C	115.0	114.0	114.0
Coal temperature °C	161.0	165.0	138.0
Rise temperature °C	46.0	51.0	28.0

*The heat current had been turned off at power house. Coals were left two days longer.

TABLE 5

SERIES 4—WET COAL—3 PER CENT PYRITE

	Coal 0	Coal 0–$\frac{1}{8}$	Coal $\frac{1}{8}$–$\frac{1}{4}$
Time in hours	72.0	72.0	72.0
Oven temperature °C	39.5	40.0	39.5
Coal temperature °C	39.5	39.2	42.3
Rise temperature °C	0.0	....	2.8
Time in hours	72.0	72.0	72.0
Oven temperature °C	60.0	60.0	61.0
Coal temperature °C	56.5	55.7	66.5
Rise temperature °C	....	....	5.5
Time in hours	72.0	72.0	72.0
Oven temperature °C	80.0	80.0	80.0
Coal temperature °C	86.7	82.8	89.8
Rise temperature °C	6.7	2.8	9.8
Time in hours	72.0	72.0	72.0
Oven temperature °C	112.5	115.0	115.0
Coal temperature °C	226.2	172.0	126.0
Rise temperature °C	113.7*	57.0*	11.0

*Upon removal from the oven and standing at room temperature, the interior of the mass within the jar took fire and after a period of from 2 to 3 weeks was consumed.

TABLE 6

SERIES 5—DRY COAL—5 PER CENT PYRITE

	Coal 0	Coal 0–$\frac{1}{8}$	Coal $\frac{1}{8}$–$\frac{1}{4}$
Time in hours	72.0	72.0	72.0
Oven temperature °C	34.0	39.0	40.0
Coal temperature °C	38.0	42.4	42.0
Rise temperature °C	4.0	3.4	2.0
Time in hours	72.0	72.0	72.0
Oven temperature °C	60.5	60.3	61.0
Coal temperature °C	70.0	66.2	66.6
Rise temperature °C	9.5	5.9	5.6
Time in hours	*....	72.0	72.0
Oven temperature °C	....	80.5	81.0
Coal temperature °C	....	88.2	89.2
Rise temperature °C	....	7.7	8.2
Time in hours	72.0	72.0	72.0
Oven temperature °C	122.0	120.0	116.0
Coal temperature °C	185.0	174.0	143.2
Rise temperature °C	63.0	54.0	27.2

*Battery worn out, so regulator did not work; was recharged and put in order.

Series 4.—In Series 4 the conditions of the experiment were precisely as in Series 3, with the exception that the coal was thoroughly wet before placing in the ovens.

Series 5.—In Series 5 the conditions were the same as in Series 1 and 3, with the exception that the content of iron pyrites was increased to 5 per cent.

The first lot of coal being exhausted, a new lot was procured. This was from the same source and was hand-picked as before, but it was deemed advisable to make a careful analysis again. This analysis is shown in the following table.

TABLE 7

	Per cent
Moisture	4.34
Volatile matter	33.38
Fixed carbon	50.25
Ash	12.03
Total	100.00
Sulphur	1.17

Calculated to Dry Coal

Volatile matter	34.89
Fixed carbon	52.43
Ash	12.68
Total	100.00
Sulphur	1.22

The pyritic content of the coal was determined as before. The total iron in the coal was determined, and from it the iron soluble in dilute hydrochloric acid was subtracted; this gave the pyritic iron, and from the latter the pyrite was calculated.

	Per cent
Total iron	1.440
HCl soluble Fe	0.510
Pyritic iron	0.930
Calculated Pyrite content	1.397

The iron was determined volumetrically by the Zimmermann-Reinhardt method, as modified by Jones and Jeffery[1].

It will be noted that the pyrite content of the second lot of coal is slightly less than that used in the former series. This fact was taken into account, however, in making up the pyrite content of the coal; the pyrite used was some of the same lot that was used in making up the first 5 series.

Series 6.—In Series 6 the conditions were the same as those maintained in Series 2 and 4, with the exception that the content of iron pyrites was increased to 5 per cent. The mass was thoroughly wet down before the samples were placed in the ovens.

TABLE 8

SERIES 6—WET COAL—5 PER CENT PYRITE

	Coal 0	Coal $0-\frac{1}{8}$	Coal $\frac{1}{8}-\frac{1}{4}$
Time in hours	72.0	72.0	
Oven temperature °C	40.0	40.0	
Coal temperature °C	41.0	41.0	
Rise temperature °C	1.0	1.0	
Time in hours	72.0	72.0	72.0
Oven temperature °C	62.0	62.0	90.0[2]
Coal temperature °C	62.0	64.5	105.0
Rise temperature °C	0.0	2.5	15.0
Time in hours	72.0	72.0	72.0
Oven temperature °C	83.0	83.0	83.0
Coal temperature °C	90.0	94.0	91.0
Rise temperature °C	7.0	11.0	8.0
Time in hours	72.0	72.0	72.0
Oven temperature °C	110.5	126.0	116.0
Coal temperature °C	210.0[3]	169.0	133.0
Rise temperature °C	100.0	43.0	17.0

Series 7.—In Series 7 the content of iron pyrites was left the same as in the natural coal. It was not thought advisable to carry the amount of iron pyrites above the 5 per cent as used in Series 5 and 6, for the reason that a consistent increase in ac-

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[1] Analyst, Vol. 34, p. 306 (1909).

[2] Battery run down; was recharged; the coal was again thoroughly wet, as it had dried out.

[3] 210° was as high as the thermometer would register. Upon removal from the oven the coal took fire, as in Series 4.

TABLE 9

SERIES 7—MIXED COAL—DRY AND WET—1.40 PER CENT PYRITE

	Dry	Wet
Time in hours	72.0	72.0
Oven temperature °C	40.0	40.0
Coal temperature °C	44.0	41.0
Rise temperature °C	4.0	1.0
Time in hours	72.0	72.0
Oven temperature °C	62.0	62.0
Coal temperature °C	67.5	62.0
Rise temperature °C	5.5	0.0
Time in hours	72.0	72.0
Oven temperature °C	86.0	83.0
Coal temperature °C	101.5	89.0
Rise temperature °C	15.5	6.0
Time in hours	72.0	72.0
Oven temperature °C	110.5	110.5
Coal temperature °C	128.5	127.5
Rise temperature °C	18.0	17.0

TABLE 10

SERIES 8—MIXED COAL—DRY AND WET—3 PER CENT PYRITE

	Dry	Wet
Time in hours	72.0	72.0
Oven temperature °C	40.0	41.0
Coal temperature °C	45.5	44.0
Rise temperature °C	5.5	3.0
Time in hours	72.0	72.0
Oven temperature °C	62.0	62.0
Coal temperature °C	67.0	65.5
Rise temperature °C	5.0	3.5
Time in hours	72.0	72.0
Oven temperature °C	83.0	83.0
Coal temperature °C	95.0	93.0
Rise temperature °C	12.0	10.0
Time in hours	72.0	72.0
Oven temperature °C	148.0	147.0
Coal temperature °C	192.0	198.0
Rise temperature °C	44.0	51.0

tivity accompanies the increase of pyrites to 3 per cent, and again to 5 per cent, which seemed ample verification of the principle involved. Moreover, this latter amount approximates the limit of this substance as actually found in coals of this region. However, the variable employed in this series was the fact that sizing of the coal was not carried out. The lump material was passed through a small Chipmunk jaw crusher, set to deliver the coal in pieces not exceeding ¼ in. to ½ in. in diameter, but carrying with it a very considerable amount of dust and fine particles. Since this plan involved the use of but one sample to cover the mixture of sizes, the dry and wet mixtures were carried along parallel and are covered in the table for Series 7.

Series 8.—In Series 8 the sample of coal was prepared exactly as in Series 7, with the exception that the content of pyrites was increased to 3 per cent. Parallel jars of wet and dry coal were carried through the series as in 7.

Series 9.—In Series 9 the conditions were the same as in Series 7 and 8, with the exception that the content of pyrites was increased to 5 per cent. Parallel samples of wet and dry material were carried through as before.

TABLE 11

SERIES 9—MIXED COAL—DRY AND WET—5 PER CENT PYRITE

	Dry	Wet
Time in hours	72.0	72.0
Oven temperature °C	41.0	40.0
Coal temperature °C	47.0	40.0
Rise temperature °C	6.0	0.0
Time in hours	72.0	72.0
Oven temperature °C	62.0	62.0
Coal temperature °C	68.0	65.0
Rise temperature °C	6.0	3.0
Time in hours	72.0	72.0
Oven temperature °C	83.0	83.0
Coal temperature °C	95.0	93.0
Rise temperature °C	12.0	10.0
Time in hours	72.0	72.0
Oven temperature °C	142.0	132.0
Coal temperature °C	186.0	180.0
Rise temperature °C	44.0	48.0

Series 10.—In the foregoing series, the evidence was conclusive to the effect that with the finer sizes and the presence of iron pyrites of 3 per cent or over, together with moisture, there resulted a rise in temperature which quickly resulted, upon removal to the air, in combustion of the coal. This property was marked in both the 0 size and the 0–⅛ in. size and, since the latter was easy to prepare, it was made use of in the subsequent experiments, together with 5 per cent pyrites, for the purpose of testing the effect of various salt solutions as a possible means of checking the rise in temperature.

In Series 10, two strengths of sodium chloride solution were used with results as shown in Table 12.

TABLE 12

SERIES 10—SIZE 0-⅛—5 PER CENT PYRITE

	Wet with 3 per cent NaCl Solution	Wet with 10 per cent NaCl Solution
Time in hours	72.0	72.0
Oven temperature °C	43.0	43.0
Coal temperature °C	43.0	43.0
Rise temperature °C	0.0	0.0
Time in hours	72.0	72.0
Oven temperature °C	63.0	63.0
Coal temperature °C	63.0	62.0
Rise temperature °C	0.0	
Time in hours	72.0	72.0
Oven temperature °C	83.0	82.0
Coal temperature °C	89.0	88.0
Rise temperature °C	6.0	6.0
Time in hours	72.0	72.0
Oven temperature °C	112.0	115.0
Coal temperature °C	180.0	190.0
Rise temperature °C	68.0	75.0

Series 11—In Series 11 the same conditions were maintained as in Series 10, with the exception that 3 per cent and 10 per cent solutions, respectively, of calcium chloride were employed.

TABLE 13

Series 11—Size 0-⅛—5 Per Cent Pryite

	Wet with 3 per cent $CaCl_2$ Solution	Wet with 10 per cent $CaCl_2$ Solution
Time in hours	72.0	72.0
Oven temperature °C	43.0	43.0
Coal temperature °C	42.0	43.0
Rise temperature °C	....	0.0
Time in hours	72.0	72.0
Oven temperature °C	63.0	63.0
Coal temperature °C	63.0	63.0
Rise temperature °C	0.0	0.0
Time in hours	72.0	72.0
Oven temperature °C	82.0	83.0
Coal temperature °C	91.0	85.0
Rise temperature °C	9.0	2.0
Time in hours	72.0	72.0
Oven temperature °C	124.0	122.0
Coal temperature °C	184.0	148.0
Rise temperature °C	60.0	26.0

TABLE 14

Series 12—Size 0-⅛—5 Per Cent Pyrite

	Wet with Saturated Lime Water
Time in hours	72.0
Oven temperature °C	43.0
Coal temperature °C	43.0
Rise temperature °C	0.0
Time in hours	72.0
Oven temperature °C	63.0
Coal temperature °C	63.0
Rise temperature °C	0.0
Time in hours	72.0
Oven temperature °C	83.0
Coal temperature °C	91.0
Rise temperature °C	8.0
Time in hours	72.0
Oven temperature °C	124.0
Coal temperature °C	168.0
Rise temperature °C	44.0

TABLE 15

SERIES 13—SIZE 0–⅛—5 PER CENT PYRITE

	Wet with 3 per cent $NaHCO_3$ Solution	Wet with 10 per cent $NaHCO_3$ Solution
Time in hours	72.0	72.0
Oven temperature °C	43.0	43.0
Coal temperature °C	43.0	43.0
Rise temperature °C	0.0	0.0
Time in hours	72.0	72.0
Oven temperature °C	63.0	63.0
Coal temperature °C	63.0	63.0
Rise temperature °C	0.0	0.0
Time in hours	72.0	72.0
Oven temperature °C	83.0	83.0
Coal temperature °C	93.0	92.0
Rise temperature °C	10.0	9.0
Time in hours	72.0	72.0
Oven temperature °C	126.0	123.0
Coal temperature °C	174.0	161.0
Rise temperature °C	48.0	38.0

TABLE 16

SERIES 14—SIZE 0–⅛—5 PER CENT PYRITE

	Wet with 3 per cent $FeSO_4$ Solution	Wet with 10 per cent $FeSO_4$ Solution
Time in hours	72.0	72.0
Oven temperature °C	43.0	43.0
Coal temperature °C	43.0	43.0
Rise temperature °C	0.0	0.0
Time in hours	72.0	72.0
Oven temperature °C	63.0	63.0
Coal temperature °C	63.0	63.0
Rise temperature °C	0.0	0.0
Time in hours	72.0	72.0
Oven temperature °C	83.0	83.0
Coal temperature °C	93.0	95.0
Rise temperature °C	10.0	12.0
Time in hours	72.0	72.0
Oven temperature °C	132.0	124.0
Coal temperature °C	181.0	186.0
Rise temperature °C	49.0	62.0

Series 12.—In Series 12 the same conditions as to size and pyritic content were maintained, the wetting of the coal being accomplished with a saturated solution of lime water.

Series 13.—The same size of coal with the same pyritic content was employed as in Series 10–13 inclusive, excepting that the solutions used were 3 per cent and 10 per cent respectively, of sodium bicarbonate.

Series 14.—In Series 14 the conditions as to size and pyritic content were maintained as in Series 10–13 inclusive. The solutions employed, however, were 3 per cent and 10 per cent of sulphate of iron.

Series 15.—In Series 15 the principle employed was that of subjecting the sample to pre-heating at temperatures approaching the extremes attained in the ovens under the several series preceding. This series was made up as follows:

One jar of size 0–$\frac{1}{8}$, 5 per cent pyrite, dry.

One jar of mixed coal, i. e., a mixture of about equal parts of sizes, 0–$\frac{1}{8}$, $\frac{1}{8}$–$\frac{1}{4}$, $\frac{1}{4}$–$\frac{3}{8}$, and $\frac{3}{8}$–$\frac{3}{4}$, made up to 5 per cent pyrite, dry.

One jar of exceedingly fine coal, finer than ordinary dust, made by grinding the coal for 100 hours in a ball mill, the latter being a large iron jar with a porcelain lining, having a screw cover. About equal parts of coal and 1 in. to 1$\frac{1}{2}$ in. quartz pebbles were put into the jar. After grinding, the coal was sifted through a 200-mesh sieve so as to remove any small lumps, and was then made up to 5 per cent pyrite, dry.

These three jars of coal were placed in the 40° oven first and moved up after 3 days, as described previously. After being taken from the 115°–120° oven, they were allowed to cool for 3 days and then were replaced in the oven for 3 days, the rise in temperature in all cases being noted.

TABLE 17

SERIES 15
First Heating

	Mixed Coal
Time in hours	72.0
Oven temperature °C	120.0
Coal temperature °C	163.0
Rise temperature °C	43.0

Second Heating

Time in hours	72.0
Oven temperature °C	135.0
Coal temperature °C	146.0
Rise temperature °C	11.0

First Heating

	Size 0–⅛
Time in hours	72.0
Oven temperature °C	140.0
Coal temperature °C	210.0
Rise temperature °C	70.0

Second Heating

Time in hours	72.0
Oven temperature °C	136.0
Coal temperature °C	155.0
Rise temperature °C	19.0

First Heating

	Ball Mill Size
Time in hours	48.0
Oven temperature °C	69.0
Coal temperature °C	205.0
Rise temperature °C	136.0

Second Heating

Time in hours	72.0
Oven temperature °C	64.0
Coal temperature °C	73.0
Rise temperature °C	9.0

Third Heating

Time in hours	72.0
Oven temperature C	147.0
Coal temperature C	220.0
Rise temperature C	73.0

III. Discussion of Results

DISCUSSION AND PRESENTATION OF DATA

Series 1.—In order to make possible a more critical and comparative study of the various series, the temperature increases as tabulated in Series 1 to 15 were plotted in the form of curves, in which the oven temperatures were taken as the abscissas, and the rise over the oven temperatures as the ordinates. These curves shows many interesting results, and a detailed study can be more advantageously made by reference to the curves rather than to the temperature tables.

Fig. 3 shows that the temperature increase is greater as the size of the coal decreases and that most of the oxidation, assuming it may be measured by the rise in temperature, takes place above 60°C., with a more positive index of activity than at 80°. In examining these details of oxidation and the accompanying temperatures, it is very suggestive to review briefly the studies

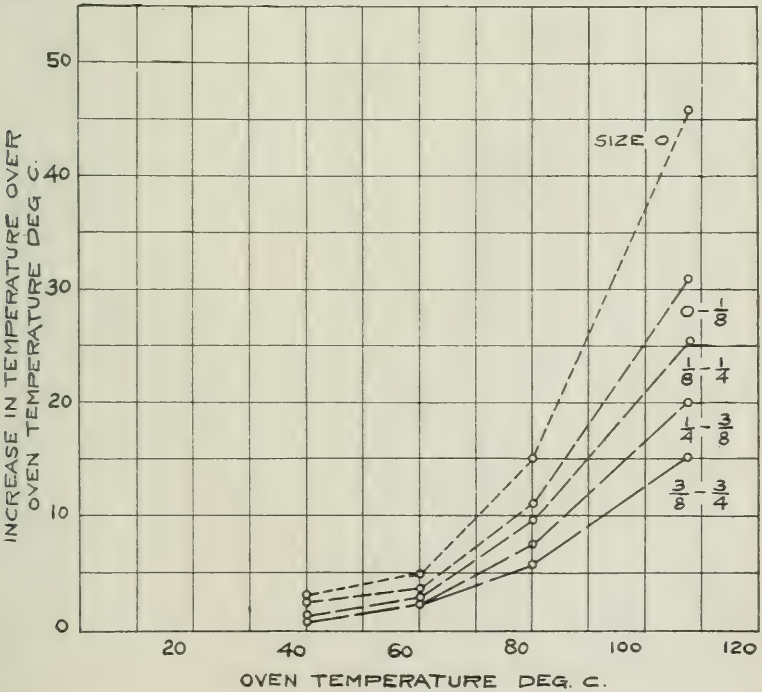

FIG. 3.
SERIES 1—1.65% PYRITE—DRY COAL.

on oxidation temperatures as carried out by Parr and Francis.[1] Those studies were conducted upon 2-gram samples of coal, suspended in an atmosphere of oxygen, with one thermometer for reading the temperature of the coal and another for indicating the temperature of the surrounding gas. In addition to the temperature rise of the coal, the appearance of carbon dioxide in the circulating gas served as an index of the starting and to some extent of the oxidation. In these previous experiments, the observed point where carbon dioxide appeared in the escaping gas was, in general, from 112°C. to 125°C., and the oxidation became so active as to show a marked increase in the internal coal temperature. From this point onward, the conditions for arriving at active combustion were quickly reached. Comparing these facts with those indicated by the curves in Fig. 3 we see a striking suggestion of chemical action other than that which results in the formation of CO_2. For example, at 80° in Fig. 3, all of the samples show a slight increase in temperature over the temperature of the oven atmosphere. It is evident that in these large 40-lb. samples a much more sensitive index of the inception of heat generation is obtained than with the small 2-gram samples of the earlier experiments, so that doubtless chemical action in some form must be considered as having commenced at a temperature considerably lower than the 110° to 120° shown in those experiments. In the present tests, it assumes positive activity quite uniformly at about 80°C.

An element not usually considered may here enter into the case, and that is the initial oxidation of coal which does not show itself in the form of CO_2. Parr and Barker[2] and also Chamberlain[3] have shown that freshly mined coals have a great avidity for oxygen, which enters into combination presumably with the unsaturated hydrocarbon compounds of the coal, and this action goes on at ordinary temperatures. Just what heat increment may be due to this action or what acceleration of the action may result from an increase of temperature has not been investigated. Doubtless, however, this initial oxidation extends over and merges into the more pronounced form, which shows itself both in the presence of CO_2 and in a marked increase in temperature. This may be a partial explanation, at least for the peculiarity of the curve in Fig. 6 of Series 3. A still more noticeable suggestion of the earlier studies on oxidation is found in the higher temperatures. For example, with the oven temperature at 108°, these larger coal masses have attained temperatures ranging from 115° to 145°, and from this latter point, the progress to ignition temperatures as indicated in the earlier tests on the small samples would be very rapid. This was found to be the case, as will be seen from a study of the subsequent experiments.

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[1] Bulletin No. 24, U. of I., Eng. Exp. Sta., June, 1908.

[2] Bulletin No. 32, U. of I., Eng. Exp. Sta., March, 1909.

[3] Bulletin No. 383, U. S. G. S., 1909.

Series 2.—From the curves of Series 2, Fig. 4, it may be seen, as expected, that any heat generated by the process of oxidation is used in driving off the water with which the coal was thoroughly soaked before putting in the ovens. At 80° C., however, we get an increase in temperature over the oven temperature, even though the coal still contains some moisture. It is to be noticed, however, that the final increase in temperature of the two finer sizes is somewhat greater than in Series 1, when the same coal was used dry.

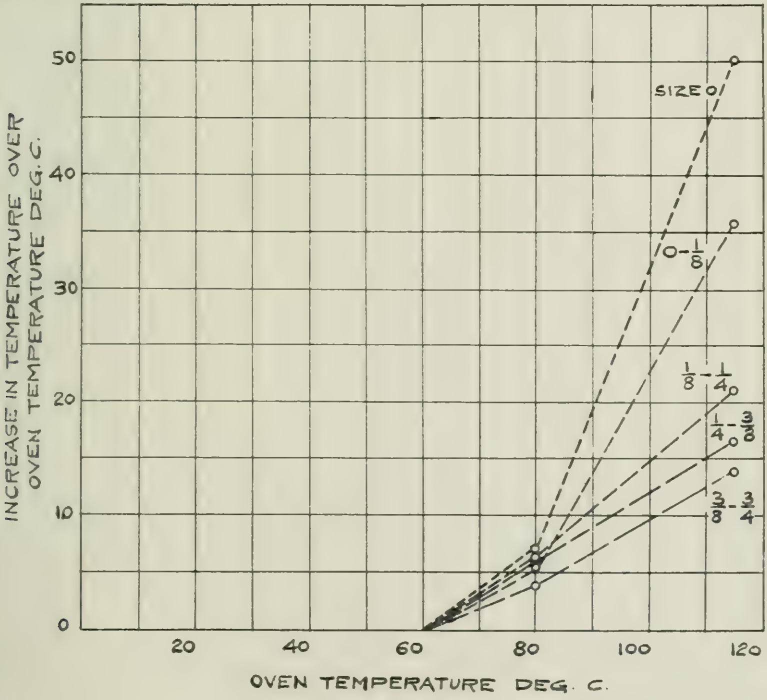

FIG. 4.

SERIES 2—1.65% PYRITE—WET COAL.

Series 3. — Fig. 5, giving the results of Series 3, shows a new and interesting phenomenon, viz., the effect of the size of the coal on the rate of oxidation. Series 1 showed that the fine coals oxidize more than coarse sizes, and also gave an indication of the rate of oxidation, although this was not noticed in time to make a detailed study of it in the first series. In Series 3, however, temperature readings were made every few hours during the time that size 0 was in the 115°–120° oven. As is seen in Fig. 5, the curve of size 0 is made up of two curves, one of which rises to an excess temperature of 75.3° and the other shows an increase of 46°, which is even lower than the temperature increase of the next size, which is 51°. The first temperature of 75.3° was reached after the coal had been in the oven only 30 hours, and from that time until the end of the 72 hours, the temperature gradually decreased to 46°, which was the final temperature. The results of this study of the rate of oxidation, as measured by the increase of the coal temperature over the oven temperature is shown in graphical form in Fig. 6.

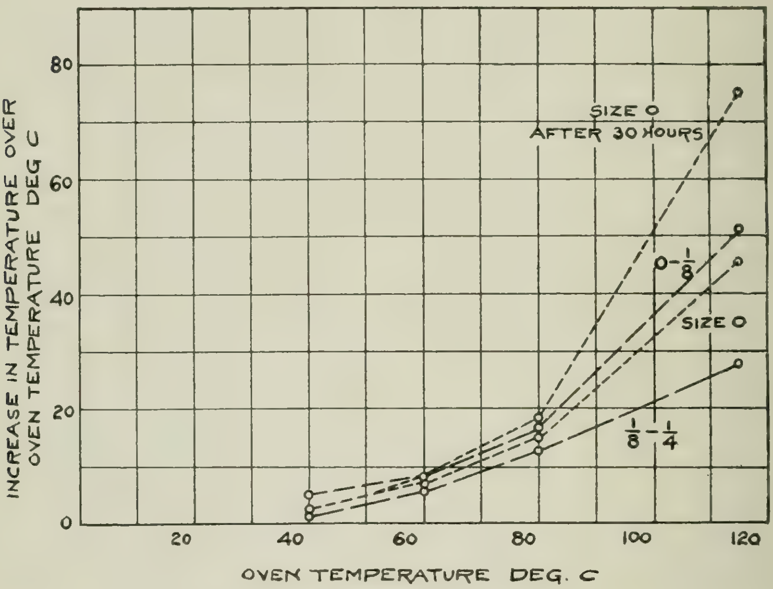

Fig. 5.

Series 3—3% Pyrite—Dry Coal.

As seen from this curve the temperature increased very rapidly during the first 30 hours, when it reached a maximum, and it is very probable that at this point this fine size of coal had satuated itself with oxygen. The temperature then gradually decreased until the final temperature was only a little more than one-half the maximum temperature attained. This phenomenon was observed only in the case of the finest size, size 0; the rise in temperature of the coarser sizes was a gradual rise over the entire period of 72 hours. If an average between the maximum and final temperature of size 0 is taken, then a consistent, though not very marked rise in temperature of Series 3 over Series 1, is noticed. These two series are the same throughout, excepting their pyrite content.

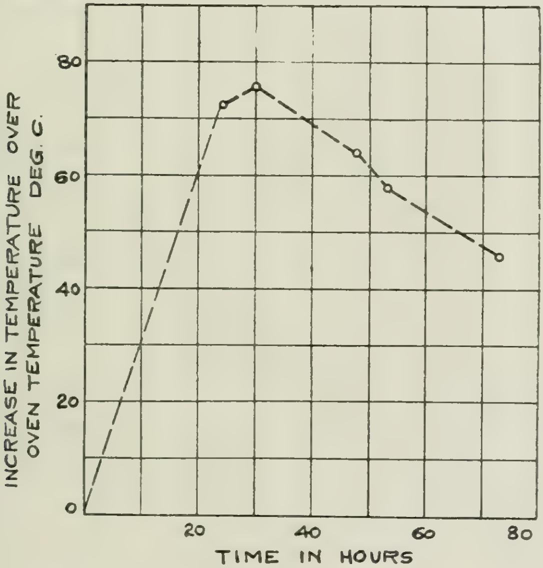

FIG. 6.

SERIES 3—3% PYRITE—SIZE 0—DRY COAL.

Series 4.—Series 4 was coal having the same pyrite content as the preceding series, only in this case the coal was first thoroughly wet. Several new points are seen. Size $\frac{1}{8}$–$\frac{1}{4}$, which was as dust free as it was possible to make it, dried out very soon and showed an increase in temperature even in the 40° and 60° ovens, whereas the two finer sizes did not even get dry at these temperatures. Size 0, at the end of three days, showed an increase over the oven temperature, of 113.7°, this being as high as the thermometers would register. On removal from the oven and on examination the following day, it was found that the coal had taken fire and that the thermometer was not far enough down in the coal to measure the total increase in temperature. The coal took fire in the middle of the jar, and, because of the slight access of air, the burning was only a slow smoldering. The jar was left out in the room temperature for about two weeks after it was taken from the oven, and was then re-examined. It was found that the coal on the interior of the jar had burned completely to an ash, although there was a ring of unburned coal all around the inside of the jar about 3 in. thick. This ring of unburned coal probably acted as an insulator for the burning coal within the jar, for being at room temperature, the coal nearest the sides of the jar was at too low a temperature to burn. After removing size 0–$\frac{1}{8}$ from the ovens it was allowed to stand in the container for several weeks, when it was found that it also had started to burn, although the combustion was not as complete as in the former case, and although the rise in temperature while in the ovens was not any greater than had been attained by some of the dry coals which had not taken fire under similar conditions. This series shows,

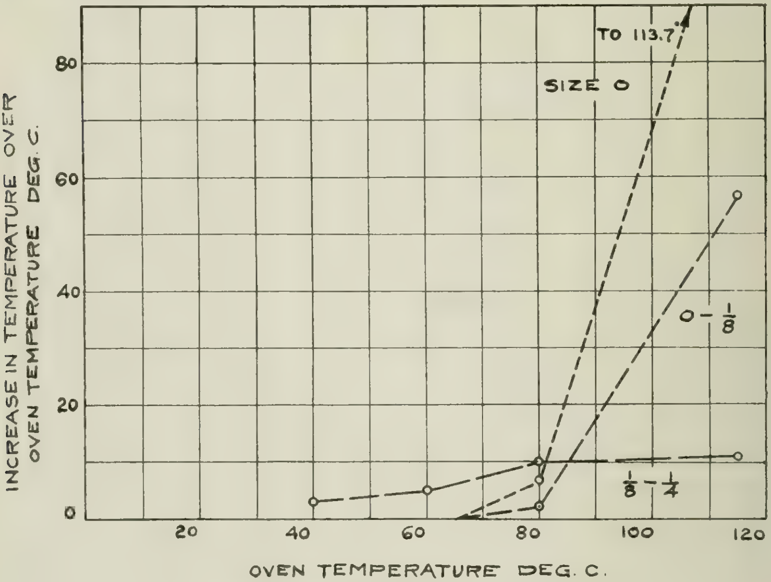

FIG. 7.

SERIES 4—3% PYRITE—WET COAL.

therefore, the effect of having the coal wet and also shows how much more dangerous and how much greater is the liability of a coal to ignite spontaneously if it has been wet. The fact that the coal in this series took fire and that the coal in the preceding series which was of the same composition did not, shows the significance and danger arising from a coal, dependent entirely upon its condition when stored.

Attention is here directed again to the former studies on oxdation by Parr and Francis[1]. In that work it was found that up to a certain point, oxidation continued only so long as the external source of heat continued, but after that point was passed, the oxidation was self-propelling, passing very quickly to the ignition stage. In the powdered sizes and in an atmosphere of oxygen, this rapid oxidation began quite uniformly at about 160°C., and soon thereafter ran up rapidly to ignition. In air, a temperature above 200° was required. This phenomenon is practically duplicated in Series 4, where the zero size of coal, after reaching 193° within the oven, had sufficient elevation to continue in its chemical activity to the ignition point upon being set out into the open air, and thus completed the demonstration of actual burning up of the sample.

Series 5.—Series 5 shows a slightly greater rise in temperature than does Series 3, and, since these two series were exactly the same in all respects except the pyrite content, it seems reasonable to suppose that the greater degree of oxidation, as measured by the rise in temperature, of Series 5 over Series 3 must be attributed in some way to the increased amount of pyrite present. It is true that the increase of temperature rise of Series 5 over Series 3 is not very great, but it is consistent in all the sizes, and as the pyrite content was the only variable in the two systems, the possibility of other factors causing an increase in temperature seems to be excluded.

Series 6.—Series 6 tends to confirm the results obtained in Series 4 in that size 0 again took fire, although size 0–$\frac{1}{8}$ in Series 6 did not show signs of active combustion as did the same size in Series 4; still it sintered together to form a cake, and in all probability would have taken fire had it been allowed to remain in the oven a little while longer. This difference in action of these two sizes in the wet series may be accounted for by the fact that size 0–⅛ in Series 6 may have had a little more water in it than the same size in Series 4, and, so may have taken a little longer time to dry

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[1] Bulletin No. 24, U. of I., Eng. Exp. Sta., June, 1908.

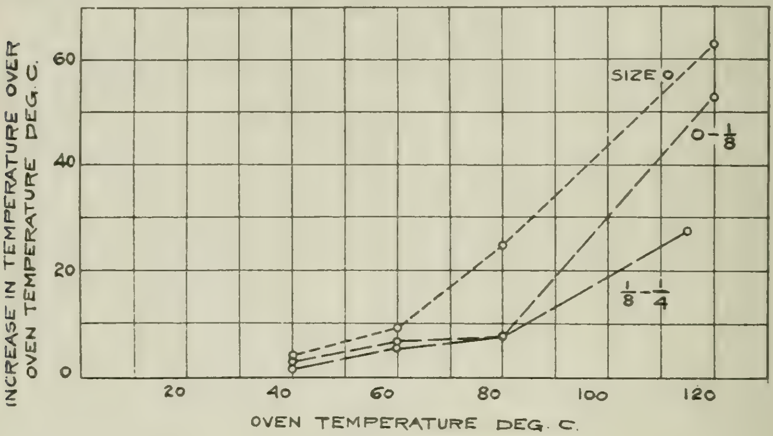

FIG. 8.

SERIES 5—5% PYRITE—DRY COAL.

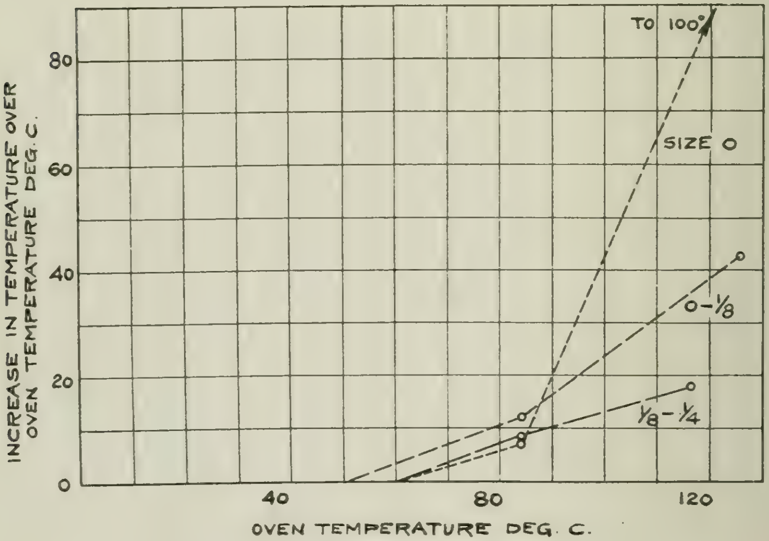

FIG. 9.

SERIES 6—5% PYRITE—WET COAL.

out, thus being in the oven a shorter length of time after it had become dry. For each size an attempt was made to use practically the same amount of water, and in the finer sizes this usually required between four and five liters. In wetting the coal, the water was added slowly with continual stirring, so as to drive out all the air, and the wet coal then had the consistency of a thick slush. The fact that the finest size of Series 4 and 6 took fire, while of the same size and having the same composition, the only difference being that the coal was dry, (Series 3 and 5), did not fire, certainly seems to prove the statements made on page 28 concerning the results of Series 4.

OXIDATION OF SULPHUR AND RESULTING HEAT INCREMENT

To determine how great an oxidation of pyrite took place, the water-soluble sulphur in the fresh coal and the various sizes of oxidized coal was determined. This was done only in Series 2, 4, and 6, where the coal had been wet, for it was thought that the oxidation of the dry pyrite would not be very great. The results are:

Water-Soluble sulphur in the fresh coal....0.0189 per cent.

Water-Soluble sulphur in the oxidized coal:

	Size 0 per cent	0–$\frac{1}{8}$ per cent	$\frac{1}{8}$–$\frac{1}{4}$ per cent	$\frac{1}{4}$–$\frac{3}{8}$ per cent	$\frac{3}{8}$–$\frac{3}{4}$ per cent
Series 2.............. ....,....	0.196	0.178	0.0317	0.0231	0.0214
Series 4..............	0.349	0.340	0.1088		
Series 6.........	0.744	0.698	0.5520		

Deducting the 0.0189 per cent of water-soluble sulphur originally present in the coal, occurs, as the result of the oxidation:

	Size 0 per cent	0–$\frac{1}{8}$ per cent	$\frac{1}{8}$–$\frac{1}{4}$ per cent	$\frac{1}{4}$–$\frac{3}{8}$ per cent	$\frac{3}{8}$–$\frac{3}{4}$ per cent
Series 2	0.177	0.159	0.0298	0.0212	0.0195
Series 4.............	0.330	0.321	0.0999		
Series 6..............................	0.725	0.679	0.5330		

If we average the water-soluble sulphur of the two finest sizes, (the coarse dust-free sizes of coal did not retain much of the finely ground added pyrite), and calculate the water-soluble sulphur to pyrite, then we can get a fair estimate of the amount of pyrite that has been oxidized to the soluble ferrous sulphate condition.

	Original Pyrite Content per cent	H_2O Soluble S per cent	H_2O Soluble S Calculated to FeS_2 per cent	Ratio of Calculated FeS_2 to Original per cent
Series 2	1.65	0.168	0.308	18.7
Series 4	3.00	0.326	0.612	20.4
Series 6	5.00	0.702	1.316	18.8

From the above table, it may be seen that even with widely differing pyritic contents, the amount oxidized was practically constant, for, as shown in the last column of the above table, about 19 per cent of the pyrite present in the coal was oxidized to a soluble condition.

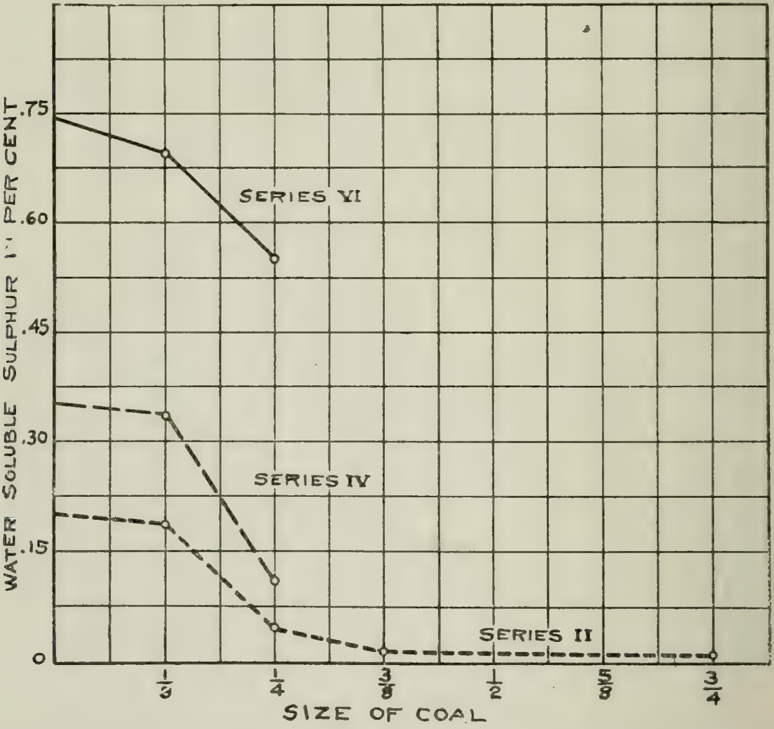

FIG. 10.

SERIES 2—1.65% PYRITE—WET COAL. SERIES 4— 3% PYRITE—WET COAL. SERIES 6— 5% PYRITE—WET COAL.

Having determined the degree of oxidation of the pyrite, it would be interesting to learn how great an increase in temperature would be due to the heat liberated by the oxidation of the pyrite, without taking into consideration the heat liberated by the absorption of oxygen by the carbonaceous material. Pyrite oxidizes according to the following equation:

$$2FeS_2 + 7O_2 + 2H_2O = 2FeSO_4 + 2H_2SO_4 + \text{heat.}$$

It is true that the oxidation goes further: the final product is probably a mixture of ferric sulphate ($Fe_2(SO_4)_3$) and basic ferric sulphate ($Fe(OH)SO_4$), and this would tend to increase the amount of heat liberated. Also, some of the free sulphuric acid formed would combine with some of the basic materials present in the coal, such as lime or alkali, but for the sake of simplicity and to be sure of obtaining a conservative or rather a minimum estimate of the effect of this heat, only the heat liberated in the above reaction was calculated. The data of the heat of formation of the oxidation of pyrite to ferrous sulphate are not yet known; at least a record could not be found in any of the standard physical-chemical authorities, but Somermeier[1] has determined the heat of combustion of pyrite to ferric oxide and sulphur dioxide, so by calculation involving known reactions, the heat liberated in the above equation is found as follows:

$$\begin{array}{rclr}
2FeS_2 + 11\,O & = & Fe_2O_3 + 4SO_2 + 373\text{ K} & (1) \\
2Fe + 3\,O & = & Fe_2O_3 + 198\text{ K} & (2) \\ \hline
2FeS_2 - 2Fe + 8\,O & = & 4SO_2 + 175\text{ K} & (1) - (2) = (2a) \\
4SO_2 + 4\,O + 4H_2O & = & 4H_2SO_4 + 256\text{ K} & (3) \\ \hline
2FeS_2 - 2Fe + 12\,O + 4H_2O & = & 4H_2SO_4 + 431\text{ K} & (2a) + (3) = (3a) \\
2Fe + 2H_2SO_4 & = & 2FeSO_4 + 2H_2 + 94\text{ K} & (4) \\ \hline
2FeS_2 + 12\,O + 4H_2O - 2H_2SO_4 & = & 2FeSO_4 + 2H_2 + 525\text{ K} & (3a) + (4) = (4a) \\
2\,O + 2H_2 & = & 2H_2O + 117\text{ K} & (5) \\ \hline
2FeS_2 + 14\,O + 4H_2O - 2H_2SO_4 & = & 2FeSO_4 + 642\text{ K} & (4a) + (5) = (5a) \\
\text{or, } 2FeS_2 + 7\,O_2 + 2H_2O & = & 2FeSO_4 + 2H_2SO_4 + 642\text{ K} &
\end{array}$$

K is used as the symbol for the large calorie, the heat liberated in each of the above equations being expressed in mols of the substance in the reactions. No account is made in this calculation of the heat of solution of the sulphuric acid nor of the hydration of the ferrous sulphate. If the weight of a jar of coal be assumed as 40 lb., (18.12 kilograms), and if the coal contains 5 per cent of pyrite, then it will contain 2 lb. (906 grams), of pyrite. The latter is 19.3 per cent oxidized, then 19.3 per cent of 906 grams will enter into the reaction (or 177 grams). The molecular weight of pyrite is 120, and two molecules entering into the reaction would be 240, hence $\frac{177}{240}$ x 642 K, or 473 K will be obtained as the heat liberated by the oxidized pyrite in 40 lb. of coal. The specific heat of the coal used is not known, but some rough experiments by Threlfall[1] show that the specific heat of bituminous coal varies from 0.3 to 0.45, with the average at about 0.35. If the specific heat of the coal used be assumed as 0.35, then the heat generated by the oxidation of the pyrite would be sufficient to raise the temperature of the coal

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[1] Jour. of the Am. Chem. Soc., Vol. 26, p. 566.

NOTE.—He finds that 1 gram of sulphur in the form of FeS_2 yields 2915 calories. Then, 2 gram-mols of FeS_2 would yield 2915 x .533 x 240 = 373 large calories.

$\frac{473}{18.12 \times .35}$ or 74.5°, which, it may be seen, is sufficient in amount to account for the larger part of the increase as indicated by the curves. Threlfall calculated the heat of oxidation of pyrite from one of Richter's experiments, the data of which were available. He also calculated the heat of oxidation of the carbonaceous material from the loss of hydrogen and carbon during the oxidation. In this experiment, the coal was heated to a temperature of 190°C. for ten hours in a slow stream of air. The oxidation of the pyrite gave enough heat to give a rise in temperature of 175°, and the oxidation due to absorption of the oxygen gave a rise of 750°, about four times as much. From these data, the total heat evolved from the pyritic oxidation does not seem important when compared with the heat liberated by the absorption of oxygen, but it is to be remembered that the absorption of oxygen by coal is immensely accelerated at an increased temperature, and it seems very probable that the pyritic oxidation may be the means by which this temperature, favorable to active oxygen absorption, is attained.

As has been shown by the work of Parr and Francis,[2] the temperature at which oxidation of the coal substance itself actually begins (about 120° in oxygen and 135° in air) is comparatively low, and therefore any influence which would serve as a force to bring the coal up to this temperature should be taken into account. Since coal is a rather poor conductor of heat the major part of the heat generated within the pile will be retained, and from the calculation of the heat generated by the pyritic oxidation, it may be seen that a sufficient quantity of heat was liberated to bring the coal up to this temperature of 135°, at which active oxidation of the carbonaceous materials begins. Of course the rise in temperature of a coal pile in storage up to 135° should not be ascribed to the effect of the pyritic oxidation alone, for it is the result of the heat liberated by the oxidation of both the coal and the pyrite. The above, however, was merely given as an example to show how great the effect of the pyritic oxidation may be.

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[1] Jour. of the Soc. of Chem. Ind., Vol. 28, p. 763.

[2] Engineering Experiment Station, University of Illinois, Bulletin No. 24.

Since the above experiments show that the oxidation of the pyrite is practically constant, that is, about one-fifth of the total pyrite present, then it follows that coals with increasing pyrite contents will have a corresponding increase in pyritic oxidation and a correspondingly greater amount of heat will be liberated. The result is a hastening of the rise in temperature up to the critical point at which the absorption of oxygen by the coal itself is rapid enough to increase the temperature up to the point of self ignition. This seems to be the explanation of the ignition of Series 4 and 6 which were identical in composition, size, and method of treatment with Series 2, except that the former contained a quantity of pyrite sufficient to cause the coal to ignite, whereas in the latter series the quantity of pyrite present was not great enough to cause this initial rise in temperature up to the critical point at which no external impetus is necessary.

It is to be remembered, of course, that in actual storage the pyritic oxidation will proceed much further than one-fifth of the total pyrite present, as in these particular experiments, but the fact still remains that the degree of pyritic oxidation in coals of various pyrite content is in direct proportion to the pyrite content so long as similar conditions of storage are maintained. It is true, certain coals containing practically no pyrite ignite spontaneously, although from the above work it is reasonable to suppose that an increased amount of pyrite would hasten the ignition. Again, the particular coal worked with did not ignite spontaneously under any conditions until the pyrite content was increased.

It seems, therefore, that the presence of pyrite is a much more important factor in the spontaneous ignition of coal than has heretofore been ascribed to it, and its influence on the spontaneous combustion of coal cannot be discarded in the off-hand way that has been so common with some of the previous investigators, merely because of the fact that some coals containing no pyrite at all would ignite spontaneously.

DETAIL OF ANALYTICAL PROCESSES FOR OXIDIZED SULPHUR

Knowing that Illinois coal contains more or less calcium sulphate, which would partly go into solution and be included in the water-soluble sulphur, it was decided to determine the ferrous sulphate actually present in the fresh coal and also the other sulphur compounds. This necessitated a complete analysis of the ash of the coal, and with the exception of the determination of the alkalies and chlorine, this analysis was made. From other analytical work on coal done in this laboratory it is known that chlorine and sodium and potassium exist in small quantities in the coal, but as the amount of chlorine present is such as to practically neutralize the alkali and, since their presence has no direct bearing upon the work at hand, these constituents were not determined.

For the analysis of the ash, two samples of 10 grams each of coal were used. These were ashed in a platinum dish, then sodium carbonate was added and the fusion completed. The fusion was put in a casserole and dissolved in boiling water, acidified with hydrochloric acid and dehydrated. The analysis was then carried out in the same manner as for any exact silicate rock analysis, with two dehydrations, volatilization of the silica with hydrofluoric acid, etc.

For the determination of iron and aluminum, the filtrate from the above,—along with the residue from the silica determination, which had been fused with potassium pyrosulphate was made alkaline with ammonia. The precipitate of the mixed hydroxides was thoroughly washed and then redissolved in hydrochloric acid, and then was made up to 250 c. c. In 50 c. c. of this solution, the iron was determined volumetrically by the Zimmermann-Reinhardt method. The other 200 c. c. were then reprecipitated with ammonia and weighed.

The calcium was determined by precipitating it as the oxalate, dissolving in sulphuric acid and then titrating with standard potassium permanganate. The magnesium was determined as the pyrophosphate. Since many of the Illinois coals also contain some calcium and magnesium carbonates, the carbon dioxide liberated from the coal by means of boiling 1:2 sulphuric acid was determined in the improved form of the Parr total carbon apparatus[1].

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[1] Eng. Exp. Sta. Uni. of Ill., Bull. No. 37 shows diagram of the apparatus.

The results of the above analyses calculated in per cent of the original air-dry coal are as follows:

	Per cent	Per cent
Silica (SiO_2)........	6.108	6.055
Ferric Oxide (Fe_2O_3)........	1.432	1.477
Aluminum Oxide (Al_2O_3 also any P_2O_5 and TiO_2)...	2.108	2.223
Calcium Oxide (CaO)........	1.576	1.571
Magnesium Oxide (MgO)........	0.123	0.117
Carbon Dioxide (CO_2)........	0.876	0.851

Numerous methods for the determination of the water-soluble iron, that is, iron in ferrous sulphate, were tried. Among these might be mentioned, digesting the coal with water both hot and cold for a period of one or two hours and also over night, using dilute hydrochloric and sulphuric acid in concentrations varying from two drops per 300 c. c. H_2O up to as high as 2 per cent acid. All these methods, however gave discordant and unreliable results.

The method finally adopted, which seemed to give the best results and which minimized the possibility of oxidation, was as follows: Three samples of 25 grams of finely ground air-dry coal were placed in large folded filter papers. About 600 c. c. of well boiled distilled water, which was practically free from air and carbon dioxide, was poured over each sample, the latter being well stirred so as to wet the fine coal thoroughly. The filtrate was then poured back over the coal, and the next filtrate, consisting of the same water as first used, was again poured back on the coal, thus making three leachings with the same water. The coal was finally washed with an additional 100 c. c. of boiling water and the total filtrate then brought to boiling. Five drops of stannous chloride solution were added, the liquid was chilled, an excess of mercuric chloride was added, and in five minutes the mixture was titrated with potassium permanganate. A blank of an equal amount of boiling, distilled water was run through the same procedure. The three titrations, which were made from a burette calibrated by the Reichsanstalt, and which was used for all volumetric work, varied 0.13 c. c. from the lowest to the highest. The results calculated to per cent of air-dry coal were:

0.0059 per cent Fe=0.0160 per cent $FeSO_4$=0.0034 per cent S. The water-soluble sulphur directly determined was equal to 0.0189 per cent, and as calculated above from the water-soluble iron was 0.0034 per cent. The difference of these two values 0.0189—0.0034 or 0.0155 per cent is some form of water soluble sulphur other than ferrous sulphate.

The next step was to determine the calcium sulphate present. This was attempted in three ways: first, since one part of calcium sulphate is soluble in about 500 parts of water, it was decided to dissolve out the $CaSO_4$ by digesting the coal with a large volume of water; second: the calcium sulphate was changed to calcium carbonate and sodium sulphate by the addition of sodium carbonate; and third, since gypsum is soluble in hydrochloric acid, a 10 per cent solution of the latter was added to the coal.

Duplicate samples of 25 grams each of coal were treated as outlined above and were put on the water bath over night. The next day they were filtered and the sulphur carefully precipitated with barium chloride after the filtrates had been concentrated. The results of the six determinations are as follows:

First Method Boiling Water	Second Method 2 per cent Na_2CO_3 Solution	Third Method 10 per cent HCl
0.0192 per cent S 0.0187 per cent S	0.0569 per cent S 0.0571 per cent S	0.0373 per cent S 0.0211 per cent S

The third method with its large variation may be discarded at once, for it seems that the solubility of the gypsum in the acid is not exact or reliable. The first method gave concordant results, but as compared with the second method they are much too low. It is very probable that after a long period of digestion the first and third methods would both give all of the $CaSO_4$ present, but as the data show, 10 hours' digestion at 100° is not sufficient. The second method gives results probably as nearly correct as can be obtained, although the solubility of calcium carbonate, which is about 50 parts in a million, would create a slight error. The sulphur obtained by the second method (as it would be from any of the three methods outlined) is, therefore, the sulphur from the ferrous and calcium sulphates. The sulphur in the ferrous sulphate, however, was determined by calculation from the water-soluble iron. The difference between these two values would, therefore, give us the sulphur present as calcium sulphate. Tabulating these results, we have:

		Per cent
H_2O soluble S calculated from H_2O soluble Fe		0.0034
H_2O soluble S directly determined		0.0189
H_2O soluble S plus S in $CaSO_4$ (Na_2CO_3 method)		0.0570
Total S in coal	1.186 1.156 1.167	Average 1.1697
S in Pyrite		0.7470

S in $CaSO_4$ = S as ($FeSO_4 + CaSO_4$) — S as $FeSO_4$

= 0.0570—0.0034 = 0.0536 per cent

0.0536 per cent S = 0.228 per cent $Ca\ SO_4$

0.0034 per cent S = 0.0160 per cent $Fe\ SO_4$

$Fe\ SO_4$ = 0.0160 per cent = 0.0034 per cent S

$Ca\ SO_4$ = 0.228 per cent = 0.0570 per cent S

FeS_2 = 1.397 per cent = 0.7470 per cent S

Total Sulphur determined....................0.8074 per cent

Total Sulphur in coal........................1.1697 per cent

Sulphur unaccounted for and probably existing as organically combined S.....0.3623 per cent

Since the coal used contained 0.863 per cent of carbon dioxide which was liberated on the addition of acid, this carbon dioxide must therefore exist in the original coal in the carbonate condition, very probably as the carbonates of calcium and magnesium. 0.864 per cent of CO_2 is equivalent to 1.965 per cent of $CaCO_3$. The calcium oxide (CaO) as determined in the ash analysis was 1.574 per cent, which is equivalent to 2.807 per cent of $CaCO_3$.

The difference between these two values, 2.807—1.965 = 0.842 per cent of calcium measured in terms of calcium carbonate, is unaccounted for and probably exists as calcium silicate and calcium sulphate.

The above has all the CO_2 calculated to $CaCO_3$, but in reality the coal contains 0.120 per cent of magnesium oxide (MgO), which probably exists as the carbonate, so 0.120 per cent MgO is equivalent to 0.251 per cent $MgCO_3$ or 0.131 per cent CO_2. Deducting this CO_2 from the total CO_2, it would give the CO_2 equivalent to $CaCO_3$.

0.863 per cent total CO_2
0.131 per cent CO_2 equivalent to MgO and $MgCO_3$

0.732 per cent CO_2 which is very probably all $CaCO_3$
0.732 per cent CO_2 = 1.665 per cent $CaCO_3$
Total $CaCO_3$ from CaO = 2.807 per cent
Total $CaCO_3$ from CO_2 = 1.665 per cent

1.142 per cent of $CaCO_3$ existing as $CaSO_4$ and $CaSiO_3$.

$CaSO_4$ as determined = 0.228 per cent equivalent to 0.167 per cent of $CaCO_3$.

1.142 per cent—0.167 per cent = 0.975 per cent $CaCO_3$ existing as $CaSiO_3$.

0.975 per cent $CaCO_3$ is equivalent to 1.112 per cent $CaSiO_3$.

Summing up the above combinations:

$MgCO_3$	0.251	per cent
$CaCO_3$	1.142	per cent
$CaSO_4$	0.228	per cent
$CaSiO_3$	1.112	per cent
$FeSO_4$	0.0160	per cent
FeS_2	1.397	per cent

The remainder of the iron and silica in the ash is probably present as earth or basic iron silicates with some free silica. The ultimate analysis of the ash sums up to 11.387 per cent. The ash, as determined from an average of four determinations, (varying 0.070 per cent from highest to lowest) is 12.030 per cent; the difference of 0.643 per cent is alkali, chlorine, and probably a small amount of combined carbon dioxide, for the ash was determined by blasting to a constant weight in a porcelain crucible and was not carried to complete fusion in platinum.[1]

From the data presented, it may be seen that the oxidation of pyrite in fresh lump coal is very slight, and that the sulphur obtained as water-soluble sulphur consists of the mixed sulphates of iron and calcium. The meaning of the term water-soluble sulphur is, therefore, necessarily vague, unless the conditions of its determination are clearly kept in mind. The solubility of calcium sulphate is great enough to cause discrepancies in the results and lead to fallacies in conclusions, unless care is taken to have conditions of determination, such as volume of water used for leaching and length and temperature of digestion always the same. Then it can be assumed, with reasonable safety, that the water-soluble sulphur determinations will all contain equal amounts of calcium sulphate. For the determination of ferrous sulphate, the determination of water-soluble iron would be the best, if the leaching is done quickly with well-boiled distilled water. The practice of digesting the coal with water for any length of time should be discouraged, for oxidation will surely set in, giving, of course, an error.

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[1] Bulletin No. 37, U. of I. Eng. Exp. Sta., Parr and Wheeler, August, 1909.

ADDITIONAL EXPERIMENTS ON MIXED SIZES OF COAL

Series 7, 8 and 9.—Having studied the effect of different pyrite contents on various sizes of coal under different conditions of moisture and temperature, it was decided to study the influence of these variables on a mixture of these sizes. For this purpose the coal was used directly as it came from the crusher; Series 7, 8 and 9 contained 1.4 per cent, 3 per cent and 5 per cent, respectively, of pyrite. The resulting rise in temperature of the wet and dry samples is shown in Fig. 11, 12 and 13. Fig. 14 is a comparative study of the three dry samples of each series, and Fig. 15 shows a similar study of the wet samples.

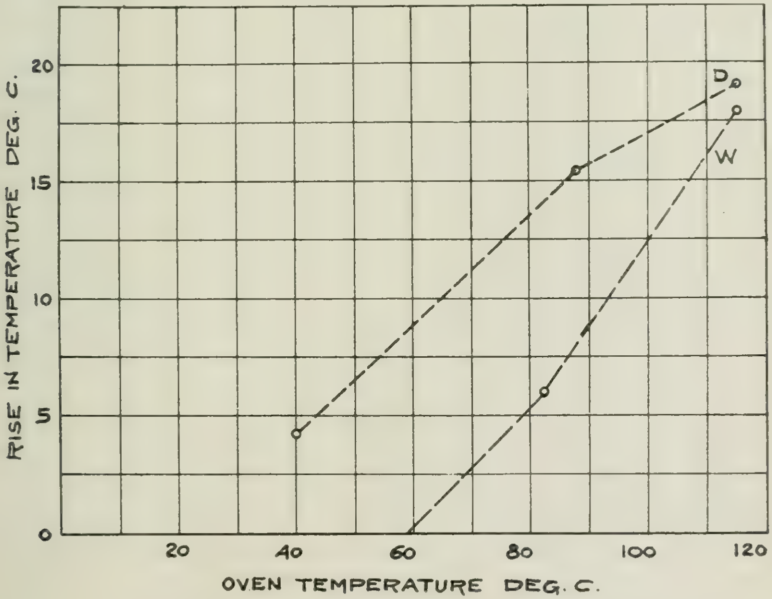

FIG. 11.

SERIES 7—1.4% PYRITE—DRY AND WET COAL.

On account of the increased amount of the larger sizes of coal in these series, the rise in temperature of the coal over the oven temperature did not approach that of some of the fine sizes of the

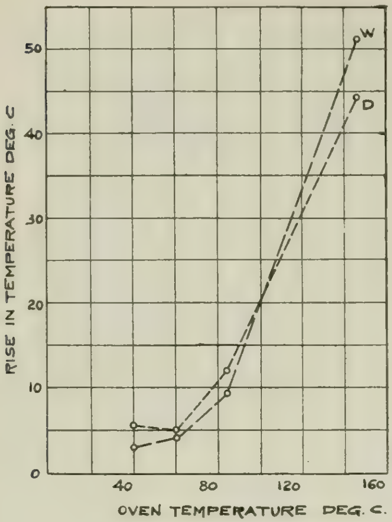

FIG. 12.
SERIES 8—3% PYRITE—DRY AND WET COAL.

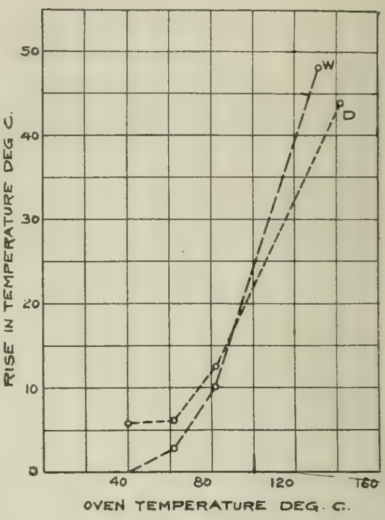

FIG. 13.
SERIES 9—5% PYRITE—DRY AND WET COAL.

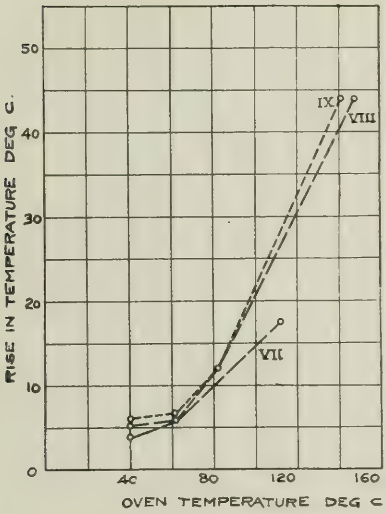

FIG. 14.
SERIES 7, 8, 9—1.4%—3%—5%-PYRITE—DRY COAL.

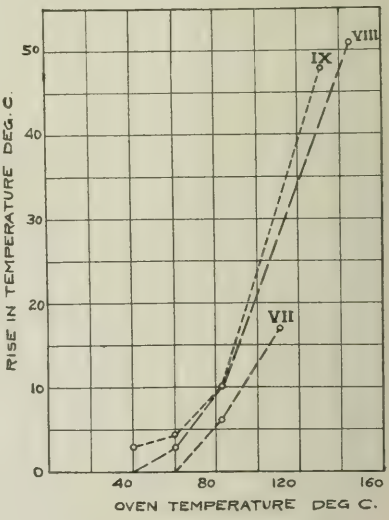

FIG. 15.
SERIES 7, 8, 9 —1.4%—3%—5%-PYRITE— WET COAL.

preceding series, but it is seen how much greater the rise in temperature of Series 8 and 9, with their greater pyritic content is over that of Series 7. This is corroborative of the facts disclosed and discussed in the preceding series, and needs no further comment, for Fig. 11 to 15 showing the results are self-explanatory. It may be argued that Series 8 and 9 showed such a marked rise over Series 7 because the oven temperature of the last oven was about 10° higher in Series 8 and 9 than it was in Series 7. This was because of a rather serious accident in the storage battery room which was of such a nature that it could not be remedied without interruption, and so spoiled Series 8 and 9; hence an attempt was made to maintain practically the same temperature as before by reducing the number of heating lights. It hardly seems reasonable, and it might be said, it is almost impossible, that an increase in oven temperature of 10° should cause an increase of the rise in temperature of about 30°, so the only variable left that could cause such a rise is the difference in pyritic content. Why this difference in behavior of these three series, which were identical in composition, size and method of treatment, should be so marked has been shown above; and all that needs to be added is that these series substantiate the results of those preceding.

A STUDY OF POSSIBLE DETERRENTS

Series 10.—Since the relative importance and the influence of the different variables under various conditions seem to have

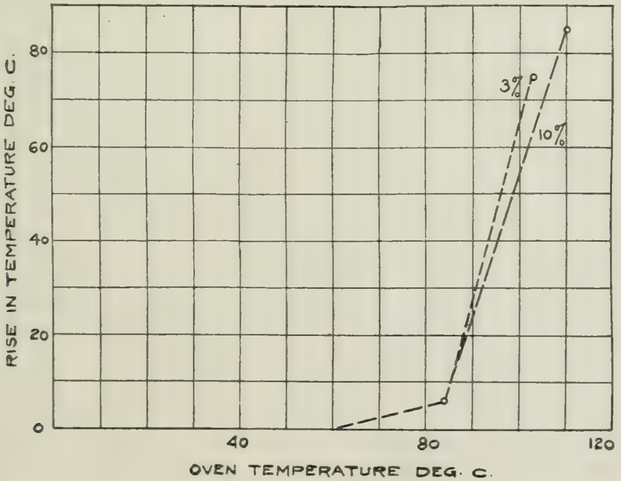

FIG. 16.

SERIES 10—5% PYRITE—SIZE 0-⅛—3%, 10% NaCl SOLUTION.

been fairly well established, it is natural that an attempt should be made to remove, if possible, this property of self ignition from a mixture of coal that had been known to take fire. As has been explained before, size 0–⅛, containing 5 per cent pyrite, was decided upon. This size of coal was thoroughly wet with different strengths of various solutions. The 3 per cent solution contained 30 grams of the salt per liter, and the 10 per cent solution contained 100 grams of the salt per liter.

The coal in Series 10 was wet with a solution of sodium chloride so as to study the effect of an inert salt, that is, inert so far as undergoing any reaction with the coal is concerned. This would, therefore, be practically the same as increasing the ash content. Fig. 16 shows that this addition of common salt exerted no retarding influence on the oxidation of the coal, the rise in temperature of the series being about 70°.

Series 11.—A solution of calcium chloride was then used. This salt is very hydroscopic and absorbs moisture with avidity and also retains it, so that it is difficult to dry anything saturated with it. The 3 per cent solution showed no retarding influence, whereas the action of the 10 per cent solution was very marked (see Fig. 17). In the latter case, a rise in temperature of only 26° took place, which shows that a solution of this strength retarded the oxidation very materially. This presumably was not because of any action inhibiting oxidation itself, but merely because so much heat was used in driving off the water.

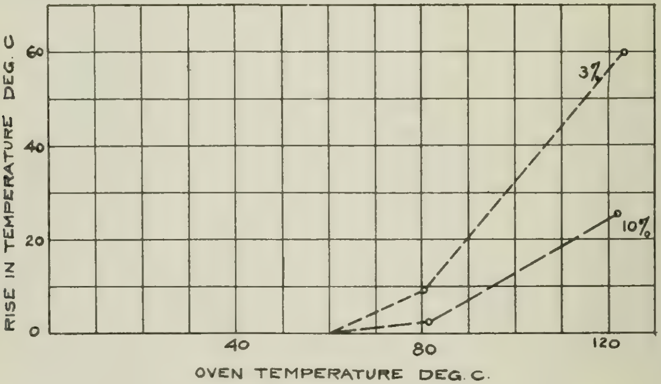

FIG. 17.

SERIES 11—5% PYRITE—SIZE 0-⅛—3%, 10% $CaCl_2$ SOLUTION.

Series 12.—Fig. 18, Series 12 shows the action of a basic substance, for in this series a saturated solution of lime water was used. The rise in temperature was not retarded to any great extent. Lime water was used to see if it would not reduce the oxidation of the pyrite, because in the weathering of the latter substance, a considerable amount of free sulphuric acid is formed. The acid would then combine with the calcium hydroxide to form calcium sulphate. A film of calcium sulphate would then cover every particle of pyrite and thus prevent further oxidation. It was hoped that this action would take place and so keep the temperature down, but the rise in temperature was greater than it was thought it would be, probably because of the heat liberated by the neutralization of the base by the acid.

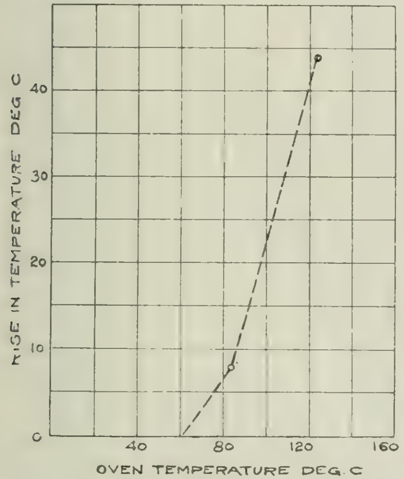

FIG. 18.
SERIES 12—5% PYRITE—SIZE 0-⅛—$Ca(OH)_2$ SOLUTION.

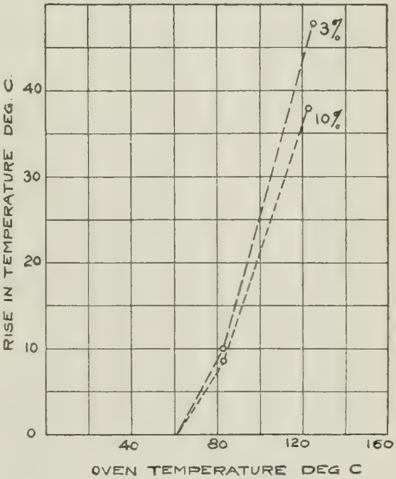

FIG 19.
SERIES 13—5% PYRITE—SIZE 0-⅛—3%, 10%, $NaHCO_3$ SOLUTION.

Series 13.—Since even a solution of sodium bicarbonate, when boiled, gives off carbon dioxide, the effect of its decomposition under a higher temperature was next studied. Also, the sodium carbonate formed would make the coal alkaline and so remove any free acid formed. As seen in Fig. 19, the 10 per cent solution has quite a retarding influence, due in all probability to the absorption of carbon dioxide by the coal instead of oxygen, and so the oxidation is lessened. It is very probable that after some time the coal would be oxidized to the same degree that it would be if the $NaHCO_3$ and CO_2 were not present, but the presence of a large amount of carbon dioxide decreases the speed of oxidation, extends the oxidation process over a longer period and so keeps the temperature down to a safe degree.

Series 14.—Ferrous sulphate oxidizes readily and quickly to ferric sulphate and basic ferric sulphate. It was thought that if a considerable amount of ferrous sulphate were added to the coal, it would be oxidixed before the coal and retard the oxidation of the latter. This was probably the case, but the heat liberated by the oxidation of the ferrous sulphate just about neutralized its retarding influence, so that the final effect was nearly the same as if the coal had been wet with pure water instead of the ferrous sulphate solution. As seen in Fig. 20, the coal wet with a 10 per cent solution gave a greater rise than that wet with a 3 per cent solution, the difference in rise of temperature probably being due to the heat liberated by the oxidation of the excess of 7 per cent of ferrous sulphate.

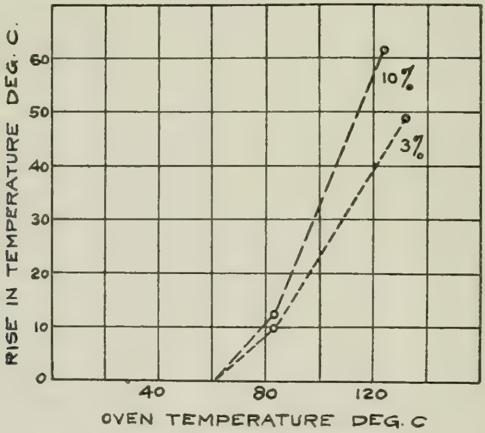

FIG. 20.
SERIES 14—5% PYRITE—SIZE 0-⅛—3%, 10% $FeSO_4$ SOLUTION.

From the above work, it may be seen that the 10 per cent solutions of calcium chloride and sodium bicarbonate retard the oxidation of the coal considerably, although whether or not a commercial application of the facts disclosed in this work on small amounts of coal is practicable or not is still to be learned from work on large storage units. Since both of these chemicals are fairly cheap, the idea seems reasonable and warrants further investigation.

Series 15.—In this series an attempt was made to determine the effect of intermittent heating and cooling, on the theory that the result of the preliminary heating would bring about those oxidation processes, which, by their cumulative effect, push the temperature up to the danger point, but, when once effected, might not be operative a second time. Three samples were thus tried out: one, (A) of mixed sizes, the same as in Series 10 to 13, with the normal amount (1.45 per cent) of pyrite present; another, (B) designated as 0–⅛ size; and the third, (C) a very fine coal dust, obtained by grinding to an impalpable powder in a ball mill. The temperature maintained by the last oven for the first or preliminary heating was 135° to 140°, with a view to carrying the oxidation along to a considerable extent, yet well short of the point of ignition. After cooling and bringing the mass up to the same temperature for the second heating, a more severe test would result than if a lower oven temperature were used. This plan was followed with all but the first sample, which had a preliminary oven-temperature of 120°. The subsequent heating, however, was carried to 140°.

The results of these tests are given in Table 17, page 22. Briefly reviewed, the results are as follows: In the first heating of the oven containing the mixed sizes, (sample A), to 120°, the coal temperature rose 43° above the oven temperature; in the second heating, the coal temperature increased only 11° above the oven temperature, even though the oven temperature was 15° higher in the second heating than in the first. Had the first heating also been up to 135°, the rise in coal temperature would have been greater than 43°, and the difference in the rise of the coal temperature over oven temperature of the two heats would also have been greater. However, the marked retarding effect of preheating is well shown in this test.

In the size 0–⅛ coal, (sample B), the difference in temperature increase between the first and second heating is much greater, due ot the finer size of coal used and also because the oven temperature in both heats was practically the same, the increase for the first heating being 70° and for the second heating only 19° or a difference in the rise in temperature amounting to 51°.

The very fine coal dust from the ball mill, (sample C), rose to 205° within 48 hours after having been put into the 60° oven. Since the ventilation of the oven was insufficient to carry off the heat as quickly as it was generated, it was impossible to keep the oven temperature down to 60°, the thermometer standing at 69°. The fact that the coal, however, maintained this oven temperature of itself even though a great amount of heat was being continually lost because of the ventilating system, shows how large an amount of oxidation took place. After cooling for 3 days and then reheating at 60°, the coal temperature rose to 73° in an oven temperature of 64°, causing only a 9° rise, whereas in the first heating at this temperature a 136° rise took place. The coal was then placed in the high temperature oven, and this oven was then heated up to 147° for three days. At the end of this time, the coal temperature was 220°, a rise of only 73° over the oven temperature. If this coal had been put into this oven first, without preheating, it would undoubtedly have taken fire at once, i. e., in 24 or 36 hours. However, as it was, the coal did not take fire until it was removed from the oven and exposed to the air. The fact that the coal did take fire after removing it from the oven shows that the time of oxidation (3 days) in the oven was not great enough to allow a thorough oxidation, although the behavior of the coal in the first two heats at 60° is of immense value in showing the effect of preheating. This particular sample of coal, ground as fine as it was, represents of course an exaggerated condition, not likely to be found under practical conditions of storage, but it was used to illustrate clearly the effect of preheating, which was shown so strikingly when the coal first indicated a rise in temperature of 136° at 69° oven temperature and then showed a rise of only 9° the second time it was heated to that temperature. It should be noted also that in the third heating, the oven temperature was sufficiently high to produce that type of oxidation which results in the formation of CO_2. This, with the marked property of condensation or occlusion of oxygen by the very finely-divided material, would be expected to result in a marked increase of temperature, quite distinct from what would occur with an oven temperature of only 60°.

To show the results on these three samples in a diagrammatic form, an attempt is made in Fig. 21, wherein the heat area is divided in the center. Points representing the increase of temperature in the first or preliminary heating are located in the left-hand area and the points representing the increase of temperature during the second heating are located in the right-hand area. In order, then to show the relation as to differences of increase, the points for the same coal in the two areas are connected by a straight line.

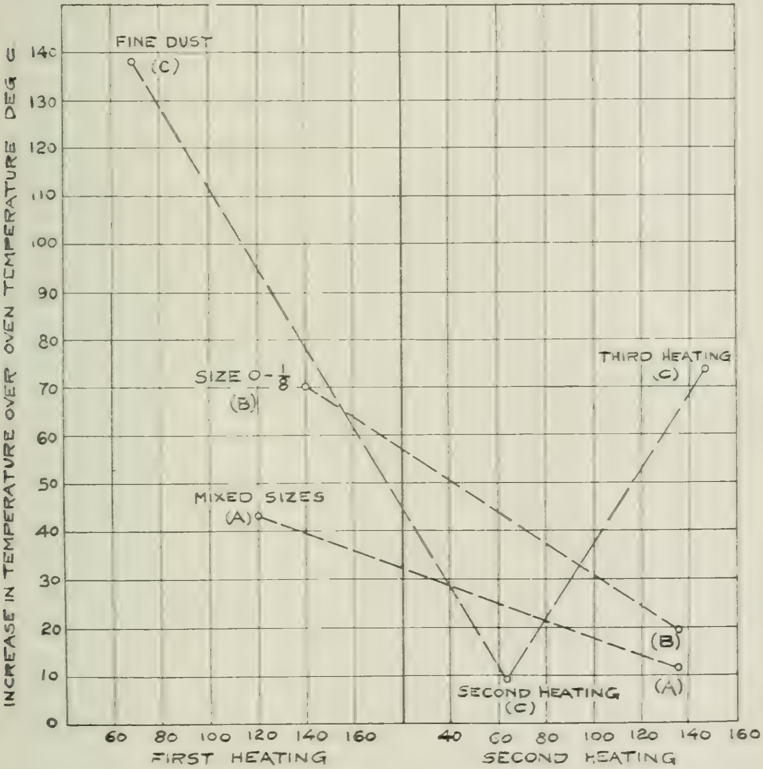

FIG. 21.
SERIES 15.

ADDITIONAL DATA

Railway Storage of Coal.—On account of the general strike of bituminous coal miners in the early spring of 1910, many of the large users of coal, such as the railroads, stored large quantities of coal for future use. In reply to a circular letter sent out for the purpose of gathering data and information concerning this coal in actual storage, Mr. P. Maher, Superintendent of Motive Power of the Chicago and Alton Railroad Company, reports as follows. A pile containing 2250 tons, 6 ft. high, 300 ft. long and 8 ft. wide, of run-of-mine, Springfield district coal, stored at Slater, Illinois, 1½ months after storage, showed 30 per cent slack, and the company was not getting results from the storage coal such as were obtained from similar coal fresh from the mine. A pile of the same kind and size of coal stored at Brighton Park, Illinois, containing 3300 tons, crumbled into 20 per cent of slack. This pile was 6 ft. high, 372 ft. long and 41 ft. wide. A pile of similar coal stored at Ridgely, Illinois, containing 19 710 tons, showed 35 per cent of slack and took fire in several places. This pile was 10 ft. high, 330 ft. long and 80 ft. wide. The reason that the latter pile took fire and the former two did not was probably due to the increased height. It is to be noted that the first two piles were 6 ft. high, while the third was 10 ft. Also, the first two piles were 8 and 41 ft. wide, respectively, while the third was 80 ft. wide. Presumably, in the first two cases, the radiation of heat in the initial stages was sufficient to keep the rise in temperature from reaching the point where the more active processes were set in motion.

IV. CONCLUSIONS

1. The oxidation of coal is continuous over a wide range of time and conditions, and begins with the freshly-mined coal at ordinary temperatures. A number of oxidation processes are involved, which are more or less distinct in character, some being relatively slow and moderate in form, while others are rapid and vigorous in their action.

2. In general it may be said that for a given coal a point exists, as indicated by the temperature, below which oxidation is not ultimately destructive. The continuance of this point is dependent upon certain accessory conditions; if these conditions are withdrawn, the oxidation ceases. On the other hand, above this critical point, which is best indicated by temperature, oxidation is ultimately destructive and is characterized by the fact that it does not depend for its continuance upon external conditions, but is self-propelling or autogenous.

3. The point of autogenous oxidation, while varying for dif-

ferent conditions, may be indicated by temperatures of the mass ranging from 140° to 160°C., in an atmosphere of oxygen, or approximately between 200° to 275°C. in oxygen diluted with nitrogen, as in air, depending to a great extent upon the fineness of division. The phenomenon of fire or actual kindling does not occur until a much higher temperature is reached, usually beyond 350°C.

4. The temperature at which autogenous oxidation begins is the sum of numerous temperature components, each one of which, either because of its own contribution to the total heat quantity or because of its function as a stimulus for chemical activities, must be looked upon as a dangerous factor, tending directly to the ultimate result of active combustion throughout the mass. An enumeration of the more important elements which contribute towards this end are the following:

a. External Sources of Heat.—Oxidation, especially of the lower or moderate form, is greatly accelerated and in certain phases directly dependent upon an increase of temperature. What may be external or physical sources of heat, and thus presumably avoidable, are suggested by the following:

(*1*) Contact of the mass with steam pipes, hot walls or floors under which are placed heat conduits of any sort.

(*2*) The heat of impact or pressure due to the method of unloading or to the depth of piling.

(*3*) Climatic or seasonal temperature at the time of storage.

(*4*) The direct absorption of heat from the sun or from reflecting surfaces.

b. Fineness of Division.—Coal in a fine state of division presents a very much larger surface and brings a much larger quantity of reacting substances in contact with oxygen than when in solid masses. Under these conditions, with a condensation or accumulation of relatively large amounts of oxygen immediately surrounding or in contact with the particles of carbonaceous matter, the circumstances are exceedingly favorable for rapid oxidation upon the arrival of the mass to a suitable temperature. But more especially does this fineness of division facilitate the initial form of oxidation described under *c* below.

c. Easily Oxidizable Compounds.—A first or initial stage of oxidation exists in bituminous coals which does not result in the formation of CO_2. There are present in coals of this type, unsaturated compounds, which have a marked avidity for oxygen at ordinary temperatures, the products being humic acid or other fixed constituents of the coal texture. Coals vary widely in this respect, and it has been proposed by some to regard this property as an index of the liability to spontaneous combustion. It is, however, very largely dependent upon the freshness of the coal and upon the fineness of division, (see *b* above,) and should be looked upon as a contributing factor, though in coals of the Illinois type, at least, with their high per cent of sulphur, this action should doubtless be considered second in importance to that of iron pyrites.

d. Iron Pyrites.—The presence of sulphur in the form of iron pyrites is a positive source of heat due to the reaction between sulphur and oxygen. This may be conveniently referred to as the second stage in the process of oxidation. Here again rapidity of oxidation is directly dependent upon fineness of division. Since coals, as a rule, have a much higher earthy or ash content in the fine duff, and since iron pyrites is a large component of this material, it follows that the presence of dust or duff in all coals of the Illinois type is a positive source of danger. Since coals of the Illinois or mid-continental field have in the larger number of cases iron pyrites averaging over 6 per cent, or, as sulphur above 3 per cent, the heat increment from the oxidation of only $\frac{1}{5}$ of this material is sufficient to raise the temperature of the mass approximately 70°, assuming that there is no loss by radiation. Under usual conditions, and especially considering the greatly accelerated rate of chemical activity accompanying a rise of temperature, this oxidation may proceed with such rapidity that the heating up of the mass will be but little affected by loss of heat due to radiation, except in relatively shallow piles.

e. Moisture. Moisture, while essential to pyritic oxidation, is given separate mention because its importance is apt to be underestimated. Any coal with conditions favorable to oxidation will be facilitated in that action by moisture. It is to be noted in this connection that the normal water content or vein moisture of coals in this region is rarely below 10 per cent and ranges usually from 12 per cent to 15 per cent. The presence of such water must be borne in mind in considering the likelihood of chemical activity on the part of the pyrites present. Without exception, in all the series of tests, *the wetting of the coal increased the activity as shown by the ultimate temperature.*

f. The Oxidation of Carbon and Hydrogen. A third stage of oxidation of the carbonaceous material exists by reason of the tendency of certain of the hydrocarbon compounds of coal to oxidize with the formation of CO_2 and H_2O at temperatures in excess of 120° to 140°. Though this type of oxidation does not take place appreciably at ordinary temperatures, it must be looked upon as an exceedingly dangerous stage in the process of oxidation, owing to the very much higher quantity of heat which is discharged by the oxidation of carbon and hydrogen; so that the temperature of autogenous action, though ordinarily occurring at a higher point by 100° or more, may be quickly attained as a result of this form of oxidation. Any initial heat increments, therefore, which threaten to bring the chemical activities along to the point where the oxidation processes invade the carbonaceous material in this manner must be looked upon as dangerous. For example, any of the initial or contributory processes which result in raising the temperature of the mass 50° above the ordinary temperature, would, in all probability, have enough material of the sort involved in such action to continue the activity until another 50° had been added, which would thereby attain to the condition wherein this third type of oxidation would begin.

g. The fourth stage of oxidation may be indicated as occurring at temperatures above 200° to 275° and differs from the previous stages in that the action is autogenous and not dependent upon other sources of heat to keep up the reacting temperature. Activity in this stage is further accelerated by the fact that above 300° the decomposition of the coal begins, which is exothermic in character,thereby contributing somewhat to a further increase in temperature. The ignition temperature is reached at a point still further along, usually in excess of 300° to 400°C.

5. The above formulation of the various stages and types of oxidation clearly indicates the principles which must be observed in any attempt at the prevention of spontaneous combustion. The following enumeration, therefore, of preventative or precautionary measures is to be considered as suggestive rather than complete in character.

> *a.* The avoidance of an external source of heat which may in any way contribute toward increasing the temperature of the mass is a first and prime essential.

b. There must be an elimination of coal dust or finely-divided material. This will reduce to a minimum the initial oxidation processes of both the carbonaceous matter and the iron pyrites. These lower forms of oxidation are to be looked upon as forces, without which it would be impossible for the more active and destructive activities to become operative.

c. Dryness in storage and a continuation of the dry state, together with an absence of finely-divided material, would practically eliminate the oxidation of the iron pyrites.

d. Artificial treatment with specific chemicals or solutions intended to act as deterrents does not offer great encouragement, though some results seem to warrant further trial in this direction.

e. By means of a preliminary heating, the low or initial stages of oxidation are effected. These sources of contributory heat being removed, the forms of destructive oxidation are without the essential of a high starting temperature and are therefore inoperative. Whether such preliminary treatment is within the realm of practical or industrial possibility could not, of course, be determined within the scope of these experiments.

f. The submerging of coal, it is very evident, will eliminate all of the elements which contribute toward the initial temperatures. As to its industrial practicability, like the conditions under *e* above, it can best be determined by actual experience.

g. Other processes may be suggested by the formulation of the principles involved. Such, for example, would be the distribution throughout the coal of cooling pipes through which a liquid would circulate having a lower temperature than the mass. This would serve to carry away any accumulation of heat and confine the oxidation to the lower stages only. On the contrary the proposition sometimes made to provide circulating passages for the transmission of air currents is of questionable value, since it may result in the contribution of more heat by the added accessibility of oxygen than will be carried away by the movement of the air.

APPENDIX

APPENDIX

HISTORICAL REVIEW WITH SUMMARY OF OPINIONS

The literature upon the spontaneous combustion of coal is widely scattered and difficult of access to a majority of those most directly interested in the topic. In this series of investigations, a considerable amount of time has been spent in assembling these discussions and making synopses of the same. In order that the results of this phase of the work may be made accessible, a review of the literature upon spontaneous combustion is presented in this Appendix.

Grundmann's[1] work, published in 1862, was probably the first serious attempt to study the weathering losses of coal. He found that while the coals lost gaseous constituents, they gained in hydroscopic moisture and so the specific gravity of the coal remained constant. He states that large pieces weather less than fine coal, and that rain and increased temperature accelerate the weathering. Using the percentage of ash as a basis to calculate the change in weight that took place during storage, he found that a pile of 300 tons lost 58 per cent in weight in nine months.

Reder[2] in 1866 was among the first to follow up Grundmann's work. He found that storing coal for a year caused a deterioration in the heating value; but, contrary to Grundmann's results, he found no appreciable loss in weight.

In 1865, Varrentrapp[3] reviewed Grundmann's work of 1862. Varrentrapp and other later workers could not duplicate the results of Grundmann, and ascribe his errors to poor sampling. Varentrapp found from his experiments in storing coal that the oxidation of fresh coal is very rapid, and within the heap leads to a rise in temperature, which, however, is very far from the ignition point.

He states, however, that temperatures reaching the ignition point and causing combustion have at times been found.

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[1] Carnall Zeitschrift, Vol. X, page 236, 1862.
Zeitschrift fur Berg, Hutten, und Salienwesen im preussischen Staate, Band IX und X.

[2] Oesterr. Zeitschrift fur Berg und Hutten, Vol. XV, 1867.

[3] Dingler's Polytechnic Journal, 1865, Vol. 175, page 168. Vol. 178, page 379.

L. Thompson[1] in 1865 found that dry coal in storage for six months lost $\frac{1}{13}$ of its calorific value; if, however, the coal was moist, the loss was much greater. He divides the weathering of bituminous coals into two classes known as "dry rot" and "wet rot". The latter he considers to be a sort of fermentation in which a part of the hydrogen escapes and some of the carbon is oxidized to carbon dioxide; in this way the coal loses calorific value in two directions.

Fleck[2] in 1865 examined a series of six Saxon coals which had been preserved in a cabinet since 1856. The results of his examination were compared with analyses made nine years previously, when, it is presumed, the coals were in a fresh state. After such an exposure in a dry place, three of the number, it was inferred, showed an important increase in proportion of ashes together with a corresponding decrease of organic matter, while the ashes of the remaining three appeared to have decreased. The explanation of such unlike results was sought by Fleck in the lack of uniformity of the related samples, especially as to the ratio of ashes. An increase of oxygen and of indisposable hydrogen was observed in each case, together with a loss of carbon and of disposable hydrogen. Hence the conclusion that, at ordinary temperatures, bituminous coal sustains a loss in carbon and of disposable hydrogen, and proportionately a loss in calorific value, which is increased in proportion to the addition of combined water.

The most careful of the early experiments made on this subject were those of Dr. Richter[3] from 1868 to 1870. He concluded that the weathering of coal was due to the absorption of oxygen, part of which goes to the oxidation of carbon and of hydrogen in the coal, and part of which is taken into the composition of the coal itself; that if the heap becomes warm, either through this process or through any other cause, the action is accelerated, but then falls off, and becomes so slow that the changes effected within a year become difficult to estimate; that moisture, as such, has no direct influence upon the process apart from the presence of pyrites or from the coal crumbling down more rapidly when wet than when dry and, therefore, more rapidly heating up; that if the temperature does not go beyond certain limits (338° to 374° F.) there is no appreciable loss of weight, but rather, on the whole, a gain through the absorption of oxygen. Also, that it is not necessary to explain the loss in heating value, of coking power, and of gas yield by any theory of new arrangements of atoms, for it is sufficient to look at the absolute loss of carbon and hydrogen and the increase in the proportion of oxygen. At a later date, he concluded that large coal was affected less than small, not because it had less surface, but because small coal was a more active absorbent of oxygen, and, therefore, became more rapidly heated; that air-ways in a heap would have to be very numerous in order to prevent any rise in temperature; and that the heap ought to be so constructed as not to allow air to get from the air-ways into the bulk of the coal.

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[1] London Journal of Arts. June, 1865, page 321.
Dingler's Poly. Journal, 1865, Vol. 178, page 161.

[2] Technik der Steinkolen Deutschlands. 1865, Vol. II, page 221.
Transactions of the American Institute of Mining Engineers, Vol. 8, page 207.

[3] The Gas World, April 13, 1901.
Dingler's Poly. Journal, Vol. 190, page 398; Vol. 195, page 315; Vol. 195, page 449.
Vol. 193, page 54; Vol. 193, page 264.

Haedicke[1] in 1880 assigned to pyrites the leading part in spontaneous ignition, conditioned on allowing the temperature to rise sufficiently.

Professor Fischer[2] of Gottingen, in his work on this subject prior to 1901 concluded that storage depreciation and spontaneous ignition were phenomena of oxidation; the part which is played by iron sulphide was disputed, but the variances which have given rise to the uncertainty were due to the differences between the different sulphides of iron present in coal. He claims that marcasite, for example, is much more weatherable than ordinary pyrite. Actual wetting is much more promotive of oxidation of the iron sulphide than heating in dry or even moist air. Besides this, Fischer finds that many coals contain sulphur in the form of unsaturated organic compounds. He finds that those coals which rapidly absorb bromine are those which are most liable to rapid oxidation and spontaneous ignition; as a practical test, he recommends shaking a gram of the finely powdered coal with 20 c. c. of a half-normal solution of bromine for five minutes. Then, if the smell of bromine has not disappeared the coal may safely be put in storage; if it has, the coal should be used up as soon as possible. The absorption of oxygen by the unsaturated organic compounds referred to is accompanied by a gain in weight and at the same time by a rise in temperature; and the warmer the mass the more rapidly does the oxidation go on, so that the temperature is apt to rise to a dangerous extent. Concurrently with the oxidation of these products, is the oxidation of another set of organic compounds with evolution of carbon dioxide and water vapor, and this results, not in a gain, but in a loss of weight. Whether the mass as a whole gains or loses weight is, therefore, a question of the composition of the coal, but the loss in weight is in no case great. Covering wet slack coal with other coal is apt to produce spontaneous ignition; the danger here appears to arise from the sulphide of iron rather than from the organic compounds. Fischer regards ventilation of the coal heap with suspicion, not because the idea is in itself a wrong one, but because it is not practicable to ventilate the whole heap efficiently. He claims that the coal should be stored dry and kept dry under cover, and in layers not too deep.

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[1] The Gas World, April 13, 1901.

[2] ibid.

In a paper read before the German Gas Association in 1900, Herr Sohren,[1] Manager at Bonn, stated that it is no longer possible for many reasons to work gasworks with a supply of coal renewed from month to month; and that all questions affecting storage have, therefore, a continually increasing importance. Undoubtedly there is a greater or less depreciation in the quality of coal kept in store, and the causes of this have attracted a good deal of attention; though, on the whole, it is surprising to find to how great an extent the study of the chemistry of coal has been neglected. Questions of this nature assumed importance in connection with the spontaneous ignition of cargoes of coal in ships; in 1874, out of a list of 4485 coal laden ships, no fewer than 60 caught fire.

In a paper read by Professor Vivian B. Lewes[2] at the 31st Session of the Institution of Naval Architects held at the Society of Arts, Adelphi, the author began by referring to the appointment of a Royal Commission in 1875 on the proposition of the Board of Trade and a Committee of Lloyds, to investigate the causes of the spontaneous ignition of coal cargoes, which had entailed serious loss of life and destruction of property. The Commission was assisted by Dr. Percy and Sir Fred Abel.

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[1] The Gas World, April 13, 1901.

[2] The Journal of Gas Lighting, Vol. 55, page 645.
The Journal of the Society of Chemical Industry, Vol. 9, page 483.

From 1875 to 1883 no less than 57 coal laden vessels were known to have been lost, while during the same period 328 were missing from unknown causes, though probably a large proportion of these losses were due to spontaneous combustion. In view of this fact, it was suggested to the author that an inquiry into the causes and possible prevention of this serious evil was greatly needed in the Royal Navy as well as in the merchant service; he therefore undertook it, and laid the results before the members of the Institute.

The author proceeded to point out that, besides the carbon hydrocarbons, coal contains certain mineral substances, as sulphate of lime or gypsum, silica, and alumina, while in nearly all kinds there is to be found disulphide of iron, "brasses" or pyrites. Of these constituents, those that are likely to produce heat and cause spontaneous ignition in newly-won coal are the carbon, hydrocarbons, and brasses, which, when they come in contact with air and moisture, give rise to certain chemical actions. He then described at length the influence of each of these substances in the production of heat. Taking carbon first, he remarked that it is one of those substances which possess to an extraordinary degree the power of attracting and condensing gases upon their surfaces, the power varying with the state of division and density of the particular form of carbon used. In the case of newly-won coals, the least absorptive would, he said, take up one and one-fourth times, and others would absorb three times, their own volume of oxygen. This absorption is very rapid at first, but gradually decreases, and is influenced to a very great extent by temperature. Air-dried coal absorbs oxygen more quickly than wet coal.

Dealing in the next place with the action of the bituminous constituents of coal in causing spontaneous ignition, the author explained that all coal contains a certain percentage of hydrogen, which is in combination with some of the carbon and also with the nitrogen and oxygen, and forms with them the volatile matter in the coal. The amount present in this condition varies very largely, being very small in anthracite and very great in cannel and shale. When the carbon of the coal absorbs oxygen, the compressed gas becomes chemically active and soon commences to combine with the carbon and hydrogen of the bituminous portions, converting them into carbon dioxide and water. This chemical activity increases rapidly with rise of temperature, so that the heat generated by the absorption of the oxygen causes the latter to enter rapidly into chemical combination. Chemical combination of this kind, i. e., oxidation, is always accompanied by evolution of heat; and this further rise of temperature again increases the rapidity of oxidation, so that a steady rise of temperature is set up. This taking place in the center of a heap of small coal, which from the air and other gases enclosed in its interstices is an admirable non-conductor of heat, will often cause such heating of the mass that, if air can percolate slowly into the heap in sufficient quantity to supply the necessary percentage of oxygen for the continuance of the action, the ignition point of the coal would soon be reached. It has been suggested that very bituminous coal (such as cannel, shale, and coals containing schist) is liable to spontaneous ignition from the fact that a rise in temperature would cause heavy oils to exude from them, and by undergoing oxidation, might cause rapid heating. Experiment, however, not only shows that this is not the case, but that the heavy mineral oils have a remarkable influence in retarding heating.

The action of iron disulphide, pyrites, or "brasses," in promoting spontaneous ignition was next discussed. The author said that ever since Berzelius first expressed the opinion that the heat given out by the oxidation of iron disulphide into sulphates of iron might have an important bearing on the heating and ignition of coal, it had been adopted as the popular explanation of that phenomenon; and, although the work of Richter clearly proved that this is not the case, the old explanation was still given. Dr. Percy in 1864 pointed out that oxidation of the coal also probably had something to do with spontaneous combustion, a prediction amply verified by Richter's researches some six years later. This disulphide of iron was found in coal in several different forms, sometimes as a dark powder distributed throughout the mass of the coal, and scarcely to be distinguished from coal itself. In larger quantities, it often occurred as thin golden-looking layers in the cleavage of the coal, while it sometimes occurred as large masses and veins, often from 1 in. to 2 in. in thickness; but inasmuch as these masses of pyrites were very heavy, they rarely found their way into the screened coal for shipment, many hundreds of tons of these brasses being annually picked out from the coal at the pit's mouth and utilized in various manufacturing processes. When the air was dry, the pyrites underwent but little change at ordinary temperatures. In moist air, however, they rapidly oxidized when in a finely-divided condition, the first action being the formation of ferrous sulphate and sulphur dioxide, together with the liberation of sulphur. The relative amounts of the latter were regulated by the temperature and the supply of air, while longer contact with moist air converted the ferrous sulphate into a basic ferric sulphate generally termed "misy". It was during this process of oxidation that the heat supposed to cause the ignition was evolved. But when it was considered that some of the coals most prone to spontaneous combustion contained only 0.8 per cent of iron pyrites, and rarely more than 1.25 per cent, the absurdity of imagining this to be the only cause of ignition became manifest. If 100 pounds of coal were taken, and the whole of the pyrites in it concentrated in one spot and rapidly oxidized to sulphate, the temperature would barely be raised to 100° C. if all loss of heat could be avoided. The author had carefully determined the ignition points of various kinds of coal, and found them to be as follows:—

Cannel	698°F.	= 370°C.
Hartlepool	766°F.	= 408°C.
Lignite	842°F.	= 450°C.
Welsh steam	870½°F.	= 477°C.

Hence, no stretch of imagination could endow the small trace of pyrites scattered through a large mass of coal, and undergoing slow oxidation, with the power of reaching the needful temperature. Richter fully realized this point, and discarded the idea of the pyrites doing anything more than adding its mite to the causes which bring about rise of temperature. In this, however, Lewes thought Richter was mistaken, his own experiments pointing to the fact that they might increase the liability to ignition when present in large quantities, and that they do so by liberating sulphur under certain conditions. A still more important part played by the pyrites, is that as it becomes oxidized to ferrous sulphate it swells in size and so tends to split up the coal into small pieces, and, by exposing a large extent of fresh surface to the air, causes increase of temperature and energetic chemical action.

The author, Lewes, then traced the actions which culminate in ignition. He said that on newly-won coal being brought to the mouth of the pit, it at once began, by virtue of its surface action, to absorb oxygen from the air. Unless piled in unusually large heaps and a good deal broken, it did not, however, as a rule, show signs of heating, as the exposed surface was comparatively small; and the air finding its way freely between the lumps kept down the temperature. The coal was now screened, and the obtrusively large lumps of brasses picked out. It was then put into trucks, and enjoyed the disintegrating processes of joltings and shuntings innumerable, every jar adding to the percentage of small coal present, and causing a corresponding increase in the size of the surface exposed to the air. Arrived at the docks, it had to be transferred from the truck to the ship, which was done by one of the numerous forms of tips, shoots, or spouts employed for the purpose; and it was during this operation that more harm was done than at any other period. The coal first shot into the vessel was, by reason of the distance which it had to fall, broken down into small lumps, and, having to bear the impact of the succeeding load falling upon it from a height, rapidly became powdered into slack; while the succeeding loads, falling in on the cone so formed, became more or less broken down so that by the time the cargo was all taken in, a dense mass of small coal was to be found under the hatchway. It was invariably at this point that heating took place, as the large surface exposed fresh to the air by the breaking down of the coal caused rapid absorption of oxygen, and consequent rise of temperature. This set up chemical combination between the oxygen absorbed by the coal, and the hydrocarbons and coal "brasses". The combination of the "brasses" with oxygen caused the swelling of the oxidized mass and the splitting up of the coal. Fresh surfaces were exposed, and more absorption of oxygen took place, the ignition point of the sulphur vapor and sulphur compounds distilled out of the pyrites was reached, and rapidly raised the temperature to the ignition point of the coal. It was only in cases where large quantities of dense coal brasses were present, however, that this action could occur. On examining the evidence to be obtained as to the conditions under which spontaneous ignition of coal ships usually takes place, Lewes found that the liability to such accidents increases with

(1) The tonnage of the cargoes,
(2) The ports to which shipments are made,
(3) The kind of coal of which the cargo consists,
(4) The size of the coal,
(5) The shipping of coal rich in pyrites while wet,
(6) The ventilation of the cargo,
(7) The rise in temperature in steam colliers due to the introduction of triple-expansion engines and high pressure boilers.

Having discussed the chemical and physical conditions which lead to the spontaneous ignition of coal, the author proceeded to formulate precautions tending to prevent such disasters. These had reference to the choice of coal for shipment to distant ports, and to the precautions to be taken during shipment and when the coal is on board. He advised that the coal should be as large as possible, free from dust, and have as little "smalls" as practicable. It should be as free from pyrites as possible, in order to prevent disintegration after shipment; and it should contain when air-dried not more than three per cent of moisture. No coal should, he said, be shipped to distant ports until at least a month had elapsed after it was brought to the surface of the pit's mouth. Every precaution should be taken to prevent the breaking up of the coal while being taken on board, and on no account should any accumulation of fine coal be allowed under the hatchways. When possible, the coal should be shipped dry, as external wetness, by producing oxidation of the pyrites, caused disintegration. When the coal had all been taken in, it should be battened down and the hatches not opened again until the vessel reached her destination, the only ventilation allowable being a 2-in. pipe just inserted into the crown of each coal compartment, and led 12 ft. up the nearest mast, the top being left open. This would be quite sufficient to allow free egress to any gases evolved by the coals, but would not allow undue access of air. Into the body of the coal cargo itself would be screwed, at regular intervals of about six feet, iron pipes, closed at the bottom and containing electrical alarm thermometers, set at a certain temperature, the attainment of which would be indicated by the ringing of a bell which would not cease until the temperature had again fallen, and then the spot in which the heating had taken place would be indicated by an index-board. The existence of overheating having been reported by the bell and recorded by the index, the author offered suggestions for suppressing it. He advocated the injection of compressed carbonic acid gas, and explained his plan as follows: The nozzle attached to the screw valve on the bottle of condensed gas would have a short metal nose-piece screwed on it, the tube of which would be cast in solid, with an alloy of tin, lead, bismuth and cadmium, which could be so made as to melt at exactly 200° F. (93° C). The valve would then be opened, and the steel bottle buried in the coal during the process of loading. The temperature at which the fusible metal plug would melt is well above the temperature which could be reached by any legitimate cause, and would mean that active heating was going on in the coal. Under these conditions the pressure in the steel cylinder would have reached something like 1700 pounds; and the moment the plug melted, the whole contents of the bottle would be blown out of it into the surrounding coal, producing a large zone of intense cold, and cooling the whole of the surrounding mass to a comparatively low temperature. The action, moreover, would not stop here, as the cold, heavy gas would remain for some time in contact with the coal, diffusion taking place but slowly through the small exit-pipe. When coal has absorbed as much oxygen as it can, it still retains the power of taking in a considerable volume of carbonic acid gas; and when coal has heated and then has been rapidly quenched, the amount of gas so absorbed is very large indeed, and the inert gas so taken up remains in the pores of the coal and prevents any further tendency to heating. Indeed, a coal which has once heated, if only to a slight degree, and has then cooled down, is perfectly harmless and will not heat a second time. It is not by any means necessary to replace the whole of the air in the interstices of the coal with the gas, as a long series of experiments shows that 60 per cent of carbonic acid gas prevents the ignition of the pyrophoric substances. One hundred cu. ft. of gas can be condensed in the liquid state in a steel cylinder 1 ft. long and 3 in. in diameter; and it has been shown that a ton of coal contains air spaces equal to about 12 cu. ft. One of these cylinders would therefore have to be put in for every eight tons of coal, and these would be distributed evenly throughout the cargo, and near the alarm thermometers, which would be set to ring a degree or two below the point at which the fusible plug would melt. The bell ringing in the captain's room would warn him that heating was taking place, and the bell would continue to ring until the cylinder had discharged its contents and had cooled down to a safe degree, so that the whole arrangement would be purely automatic, and yet the officers would know if everything were safe. If the precautions advocated were taken, no danger could arise until the arrival of the ship at her destination, and the commonest precautions would then suffice.

In conclusion, the author remarked that the question of preventing the heating and ignition of stores of coal on land and ready for use in bunkers could not be met so well by the use of the liquid gas; and in these cases it would be found beneficial to dress the coals with a little tar or tar oil, which would close the pores, and to a great extent prevent oxidation. He believed this was advocated by Lachman about 1870. Crude petroleum in small quantities would also be found valuable for this purpose, for it has no tendency to oxidize itself, and lowers the tendency in other bodies, besides coating them and so preventing access of oxygen.

In a later paper, Professor Lewes[1] of the Royal Naval College says that, in the spontaneous ignition of coal stored in bulk, the oxidation of the pyrites present plays only a very subsidiary part, the chief factor being the surface condensation of the oxygen in the pores of the coal and the action of the condensed gas in effecting the oxidation of the hydrocarbons present in the coal. While sufficient ventilation to prevent any considerable increase in temperature within the mass is effective in preventing ignition, it is practically impossible to maintain this condition in large coal stores or in a cargo on board ship, where usually only enough air enters to lead to dangerous heating. The recent suggestion to wet thoroughly the whole mass of coal is impracticable, owing to the great increase in weight brought about if sufficient water is added so as to be effective; too small a quantity of water only accentuates the danger.

A. O. Doane[2] in 1904 stated that the amount of moisture present in a bituminous fuel after drying in the air is a measure of the risk of spontaneous ignition when the fuel is stored; bituminous coals containing over 4.75 per cent of moisture are dangerous. Coal bins should be of iron or steel, protected by concrete, and should be roofed over. Free air passages should be provided around the walls and beneath the bins so as to keep them cool, and the depth of coal stored should not be over 12 ft. The customary method of providing air passages in the body of the fuel is useless, since it tends merely to accelerate oxidation and does not produce a sufficient current of air to keep the temperature down. Cracks or joints in the walls of the fuel bin increase the risk of spontaneous ignition for similar reasons.

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[1] The Journal of Gas Lighting, 1906, page 33.
The Journal of the Society of Chemical Industry, Vol.25. page 463.

[2] Engineering News, Vol. 52. page 141.
The Journal of the Society of Chemical Industry. Vol. 23. page 1203.

Durand[1] has explained the spontaneous ignition of coal as being due to the presence of pyrites, which on oxidation under suitable conditions inflames, and then sets fire to the coal in which it is embedded.

According to Fayol's experiments[2], however, the real cause of spontaneous combustion is the oxidation of the coal itself and not that of the pyrites. The absorption of oxygen by coal takes place more or less readily, depending upon the initial temperature and upon the coal being more or less finely divided. Lignite in the state of fine dust takes fire at 150°, gas coal at 200°, coke at 250° and anthracite at 300° or above. On heating a mixture of finely powdered coal and pyrites up to 200° for four days, the coal took up 6 per cent of oxygen, while the pyrites absorbed only 3.5 per cent. Hence coal absorbs oxygen much more energetically than pyrite does, a fact which was confirmed by the following experiment. 900 gr. of powdered coal and 3350 gr. of powdered pyrites were placed in tin cans and put in a drying chamber. Up to 135° both behaved similarly, but from there on the temperature of the pyrites remained almost stationary while that of the coal quickly rose, ignition taking place a few hours afterwards. Two other samples of coal and pyrites were put in a chamber at 200°. The temperature of the coal quickly increased. After 40 minutes, it reached 200°, and the coal took fire, while the pyrites had at the same time been raised only to 150°. The ignition of the coal was not at all hastened by an admixture of pyrites.

Fayol, as a result of some of his other experiments, stated that "The influence of wet weather on heaps of coal has not been sufficiently marked to be observable." On the other hand, much evidence has been given which is absolutely opposed to the above statement. In a letter to the English Commission in 1876,

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[1] The Journal of the Society of Chemical Industry, Vol. 2, page 325.

[2] Bulletin de la Societe de l' Industrie Minerale, Second Series, Volume 8, part 3, 1879

Mr. Poole[1], Inspector of Mines, Nova Scotia, makes the following remark: "Heat has been observed in piles of slack coal that have been accumulated during the summer for the use of engines during the winter, when the season has been showery, but not when it has been dry." Much similar evidence was offered the English Commission; for, out of the 26 answers to questions as to the effect of moisture, every reply was to the effect that moisture was a source of danger. Similar evidence was given at the inquiry held by the New South Wales Commission, although, on cross examination, it was brought out that this view was more a matter of impression than of definite knowledge.

Fayol[2] also found that the coal of Commentry never took fire by exposure when the heaps were less than two meters deep, no matter what the lateral dimensions of the heaps might be. He also found that a mixture of dust and fragments was the most dangerous.

Some valuable evidence on the subject of the size of the storage heap was given to the New South Wales Commission by Mr. Bush[3], the engineer of the Australian Gaslight Company. It appears the Australian Gaslight Company has two coal stores, one at Kent St., and the other at Mortlake. These stores are kept more or less full for gas making. The Kent St. store is filled with coal to a depth of 14 feet, the Mortlake store to a depth of 20 feet. The Mortlake store requires great care to prevent the coal from firing, whereas no case of firing from spontaneous combustion has occurred at Kent St. All other circumstances are, so far as known, exactly the same at both stores. The opinion of Mr. Bush is that the difference in the behavior of the coal in the two stores is to be attributed to the difference in depth of the coal.

"It was formerly supposed[4] that the oxidation of pyrites (a common impurity of coal) is the initial cause of spontaneous heating. This, however, has been disproved in many tests by direct experiment, and it also appears that there is no direct relation between the pyrite content of coal and its liability to spontaneous combustion. On the other hand, if coal is wet, it has been shown that the pyrites tends to oxidize, and in so doing may help to break up the coal and thus render it more liable to spontaneous combustion by increasing the surface. We are of the opinion, however, that the cases of spontaneous combustion of Newcastle coal are not in any way traceable to this action, since we have not been able to find that the cargoes which have fired have been unusually wet, or that the sulphur content was unusually high; in fact, the average sulphur content is only about 0.5 per cent.

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[1] Threlfall, On the Spontaneous Heating of Coal, Jour. of the Soc. of Chem. Ind., Vol. 28, p. 763, 1909.

[2] For an excellent review of Fayol's monumental work on the coals of Commentry, see 1.

[3] Report of the First New South Wales Commission.

[4] From the Introduction to The Report of the First New South Wales Commission, inquiring into the causes of the firing of coal cargoes, etc.

"It still must be regarded as an open question, however, whether the heating of Newcastle coal is in any way dependent on the amount of moisture which it contains. On the other hand, we have the very definite experimental result of Fayol that moisture has no influence whatever on the liability to spontaneous combustion of the coal of Commentry, and yet we see that the disintegrating action of oxidizing pyrite may have an indirect effect.

"Most of the witnesses we examined were of the opinion that wet coal was more likely to fire; and some important evidence was given us by Mr. A. Ross, manager of the Wallsend Mine (Ans. 1379), and also by Mr. Reed, screen overseer, in charge of the hoppers in which the Newcastle-Wallsend Coal Company store their small coal. These witnesses stated that the temperature of the coal in the Wallsend hopper increased within a few days after a shower of rain. On visiting the hopper and digging into the coal to a depth of two or three feet, we obtained samples of coal, some hot and moist, some cool and dry. The place from which the hot sample was obtained was distant only a few feet from the place where the cool sample was taken. Chemical examination disclosed no appreciable difference between the two samples. It occurred to us that possibly the hot coal had been heated by distillation of steam from the coal below, which coal was spontaneously heated, and this we are inclined to think was really the case, for the seat of spontaneous combustion is never within three feet of the surface of a heap of coal. On drawing Mr. Reed's attention to the possibility of this explanation, he appeared inclined to agree with us (Q. 3426-8). We consider it not unlikely that the heating up of otherwise unheated coal by the distillation (and condensation) of steam may have given rise to the idea that moisture is favorable to spontaneous heating.

"Of course, if coal is red hot and small quantities of water are poured upon it, the resulting steam is decomposed by the red hot coal, and the carbon monoxide and hydrogen thus liberated burn with flaming. This fact, also, we are inclined to think may have tended to give rise to the impression that moisture assists the spontaneous combustion of coal.

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"It is, perhaps, obvious from what has been said on the subject of the absorption of oxygen by coal, that a very important condition is the initial temperature of the coal. From two cases which came under our notice, we are inclined to think that the masters of ships are not sufficiently alive to the importance of keeping the coal away from the hot surfaces, especially when the surfaces are themselves far below the ignition point of coal. A donkey-engine and boiler, for instance, may be separated from the hold by a cement floor laid on the deck planking, and so far as we could ascertain there seemed to be an impression that the heat which could be transmitted through such a shield could have no ill effect on the coal. The fact is, however, that the rate of absorption of oxygen increases so greatly with rise of temperature that the moderate warming of the coal by a steam pipe or boiler may enormously shorten the time necessary for spontaneous combustion to set in, or may render spontaneous combustion possible in cases where it would otherwise be impossible."

These remarks apply with great force to the practice of loading coal in very hot weather. The coal lying in trucks on the dyke and exposed to the sun is loaded at a temperature which it might take months to reach if it had to generate the necessary heat by absorption of oxygen. This reasonable conclusion is supported by the fact that three very large ships were loaded together during the hot weather of January, 1896, and all of them were the victims of spontaneous combustion.

The acceleration of the rise of temperature consequent on a large initial temperature is also well illustrated by the cases of the "Knight of St. Michael", the "Morna", and the "Invernay", all of which were loaded during extremely hot weather, and all of whose cargoes became dangerously heated within a short time of loading.

The United States Admiralty[1] has made experiments and gives valuable directions for preventing the spontaneous combustion of coal. Anthracite is excluded from the inquiry since only bituminous coals are liable to catch fire. The ignition of coals may be induced by condensation and absorption of the oxygen of the air by the coal, whereby the temperature is raised so high that chemical combination between the hydrogen and oxygen can take place. This easily happens if the coal be very pure and brittle, if the outside temperature also be high, and the necessary ventilation be wanting. Another cause of ignition is the action of moisture on the sulphur of many pyritic coals, not so much from the heat of the chemical reaction as from the circumstance that the coal is split and broken up, and so fitted for the absorption of oxygen.

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[1] Oesterr, Zeits. Fur Berg und Hutten. Vol. 47, page 78.
The Journal of the Society of Chem. Industry, Vol. 18, page 568.

The arrangements for preventing ignition on board ship are not taken up, but it said that on land it is mostly the pyritic coals that take fire. Care should be taken that the coal is stored on iron floors, and covered, the height of the heap not to exceed two to two and one-half meters. For sea voyages, the coal should not be loaded earlier than one month after it has been mined.

Mr. Stelkins[1], in his report before the International Navigation Congress in 1902, stated that the tendency towards spontaneous ignition of coal increases with the height to which the coal is piled. Stacks higher than 15 ft. should not be made. Rain during and after stacking and compression caused by dumping coal from a great height on the stack, all add to the danger of ignition.

Mr. F. M. Griswold[2] of the Home Insurance Company, in 1904, states that spontaneous ignition is more marked in free burning or so-called "high steaming coals" including "gas coals". These coals usually contain a large amount of volatile matter and small amounts of oxygen. The tendency towards spontaneous ignition increases when sulphur or lignites are found in the coal and especially when pyrite is present. Slack, mine run, and dirty coal are dangerous because of the fine particles present, the latter gradually sifting to the bottom and being compressed.

According to Mr. Griswold, a satisfactory explanation of spontaneous ignition and combustion of bituminous coal has not as yet been made. The best authorities say it is due to chemical changes in the substance of the coal resulting from the absorptive powers of carbon, the latter increasing with the rise in temperature. Rise in temperature may be due to the chemical action caused by slow oxidation or to the mechanical force of pressure: both of these conditions may be stimulated by moisture and the presence of pyrites. Some claim that over $2\frac{1}{2}$ per cent of sulphur in the form of pyrite is dangerous. Various tests have been proposed to determine the liability of a coal to heat, such as the gain in weight of the coal at 250° F. and the absorption of bromine, but these tests are not valuable, as it is difficult to tell how much oxygen the coal has already absorbed. He recommends that no wood be used in the construction of bins, that all ironwork be covered with concrete, that no steam pipes or flues be near the bins, that a good circulation of air be about the sides and under the bins, and that the coal should not be piled to a depth greater than 12 ft. He also recommends that the bins be roofed, and that they contain pipes in which thermostats should be placed, and when the latter register 140° F., something should be done to stop the rise in temperature.

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[1] American Society of Naval Engineers, February, 1901

[2] Engineering News, November 10, 1904, page 409.

A. E. Dixon,[1] in 1906, stated that spontaneous ignition occurs with friable bituminous coal, and particularly with those grades containing brasses or iron pyrites; when the coal is damp, the trouble is increased. The cause is probably due to the absorption of oxygen by the carbonaceous material, just as is the case with oily cotton waste.

An article describing the coal storage department of the works of the Lackawanna Steel Company[2] says "Derricks are used to pile the coal and they are able to pile it to a height of 60 feet; but to avoid spontaneous combustion, it was deemed advisable to restrict the height of the piles to 20 or 30 feet."

Mr. Peter Bullock[3] cites several cases of coal piles catching on fire, seemingly due to spontaneous combustion. In all, about ten or twelve cases were cited; about half of these cases he believes to be due to heating from steam pipes which were near by, for the others he gives no explanations.

Groves and Thorp[4] state that gases occluded in the crevices or cavities of the coal escape during mining and continue to do so after storage. The inflammable nature of these gases makes them a source of great danger, for it is believed that they are the causes of many of the disastrous explosions on board vessels carrying coal as a cargo.

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[1] Engineering News, November 10, 1904, page 409.

[2] Engineering Record, July 4, 1903.

[3] Power, 1908, page 675.

[4] Groves and Thorp, Chemical Technology, page 82.

Parr and Barker[1], working on the gases occluded in Illinois coal, found that two active processes are set up immediately upon liberation of the coal from the vein. The first is an exudation of hydrocarbons, consisting mainly of marsh gas (CH_4), and the second is an absorption of oxygen. They found that after a period of two months practically all of the marsh gas had been liberated and, although the avidity of the fresh coal for oxygen was very pronounced, after a period of two months, active absorption of oxygen still took place.

The work of R. T. Chamberlin[2] on explosive mine gases and dusts confirms the above work of Parr and Barker. Working on the gases occluded in the coals of the Naomi, Monangah and Darr mines of Pennsylvania and West Virginia, the author found that after the extraneous nitrogen had been removed, methane was by far the most important gas which escaped from the bottled coal. In some tests it ran as high as 98 per cent of all the gas coming from the coal; more commonly, however, it constituted from 80 to 95 per cent of the gas liberated. The finely crushed coals gave out methane at a very rapid rate, practically all of it in a period of 8 or 10 weeks, whereas the small lump coal gave out the methane at a slow uniform rate, although after a period of 26 weeks the total volume of methane given off almost equaled that given off by the fine coal.

Working on the comparative inflammability of coal dusts from the three mines mentioned above, within a few days after the unusually violent and fatal explosions which swept all three, the author points out some valuable facts concerning the absorption of oxygen by coal. He found that comparatively little oxygen can be extracted from coal, although very large volumes of oxygen are rapidly and steadily absorbed by the coal. The experiments with coal dust indicate that, with exposure to the action of the air, there is a development of the oxides of carbon and sulphur within this dust, or of compounds which give off these gases at moderate temperatures. Coal bottled in air for a few weeks gives off a much higher proportion of carbon dioxide than if placed in a vacuum; but it does not give off as carbon dioxide, within a short time at any rate, more than a small percentage of the oxygen absorbed from the air in the bottle. Air bottled with Illinois (Cardiff mine) coal for two weeks contained at the end of that time only 1.05 per cent of oxygen and 1.59 per cent of carbon dioxide, together with 0.62 per cent methane and 96.74 per cent of nitrogen. Thus only a small proportion of the oxygen which goes into coal comes out again as carbon dioxide. The formation of water by the oxidation of a part of the hydrogen in the coal is a natural explanation for the apparent disappearance of some of this oxygen. It may also be that some of the organic compounds have been only partly saturated and hence the oxygen absorbed is not given off at once as carbon dioxide, but comes off later when the oxidation has progressed further.

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[1] University of Illinois, Engineering Experiment Station, Bulletin No. 32, 1909.

[2] Bulletin 383. U. S. Geol. Sur. "Explosive Mine Gases and Dusts", 1909.

Dennstedt and Bünz in 1908[1] exaggerated the conditions of spontaneous combustion by passing oxygen through a sample of coal at 135° or 150°C. The coals tested by them are divided into four classes:—

1. Coals whose temperature never rises above that of bath.
2. Coals that rise only slightly above the bath temperature.
3. Coals that rise fairly high, but will not take fire unless the oxygen supply is carefully increased with the rise in temperature.
4. Coals that take fire easily, usually in about two hours. Six typical coals were selected to determine what chemical variations accompanied the above classes. They found that coals that have been thoroughly wet kindle more rapidly than if they have been kept dry. Quoting their conclusions, we find: “Self-ignition increases in a ratio corresponding to the amount of moisture in air-dry coal; mechanically combined moisture is not meant, for the coals used gave the impression of being perfectly dry; the moisture seems to be water of constitution.

Surface absorption has the same degree of importance as the above water of constitution. The question certainly is not one of hydroscopicity, or of the hydroscopic inorganic salts present, for water-soluble mineral salts are found in very small quantities in all coals, so small that they do not even increase the surface absorption.

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[1] Zeitschrift fur ang. Chemie, 1908, Vol. 21, p. 1825-35.

Moisture and its reabsorption are allied to, or controlled to a certain extent by, the organic substances and their composition. It may also be noticed here that the humic acids formed in the coals are exceedingly hydroscopic. But these cannot cause the surface absorption in the original coals, because no completely formed humic acids are present; therefore the increased surface absorption of the oxidized coals is undoubtedly due to the humic acids. The increasing Maumene number (with increasing self-ignition) is also in accordance with the idea of water of constitution, and here it is also seen that the organic substances have an influence, for the Maumene number increases in the same ratio, even in those coals that are dried in a current of carbon dioxide. It is very remarkable that these coals, dried in this way, should cause a rise in temperature when they are stirred in cold water (this property increases as self-ignition increases). The Maumene number can, therefore, well serve as a standard which would decide a coal's power of self-ignition.

Neither amount nor kind of mineral substance nor pyrite found in coal has any effect on the self-ignition; this is seen without a doubt from a consideration of the analytical data. The pyrite content is very small, and besides the pyritic coals are not the easiest to self-ignite. One could also think of certain catalytic actions; to this effect there were made numerous observations upon coals which had caused fires, and they had only a very small amount of pyrite that occurred in a fine condition. This pyrite was found in a slaty portion of the coal and upon fresh cleavage fractures in the form of a fine sulphur-colored film. But the fact that just such coals, which are very easily self-ignitible, such as Scotch coal No. 6, contained a minimum quantity of pyrite, carries one away from the above idea. The same might be thought of the hydrochloric acid soluble iron in the original coal,—that this might be due to a catalytic action, but here also the amount is small and does not grow with the degree of self-ignition so that it was not thought necessary to insert the analytical data in the tables. One could rather speak of the water-soluble iron in the oxidized coal as due to this cause; sometimes in coals that have been stored for a long time and perhaps have become wet too, an oxidation of pyritic iron in the form of basic sulphate is found, but we did not find any increased self-ignition in them."

From the above, it seems without a doubt that the organic substances control the self ignition of coal, and it depends not so much on the amount but rather upon the kind and composition. This follows directly from the ultimate analysis; of course, the amount of organic combined sulphur and nitrogen has no effect. For it is seen that neither is found in any great amount in coals that are easily inflammable over coals not easily so. With the sulphur one could think of the formation of easily inflammable compounds, for example, carbon bisulphide. During the oxidation process, carbon bisulphide was expected, but no trace was found. Very conspicuous in the elemental composition is the proportionately small amount of hydrogen in the more inflammable coals, and the particularly larger amount of oxygen which is especially noticeable in the small amount of available hydrogen.

Quoting further from these writers:—"If the self-warming and ignition are caused by this oxidation, which we believe has been shown, then at first glance it seems a contradiction that those coals already so rich in oxygen are the most easily oxidized. But when one thinks that all coals are finally tending toward a similar or equal character or composition, then one can easily picture that a transition period of marked inflammability exists, which the easily inflammable coals have already reached. This is in accordance with the remarkable properties of the coals in Class II, which with preparatory treatment at 135°C. with oxygen, become more easily inflammable. This point seemed to be of sufficient weight to cause certain quantitative experiments to be made so as to prove it. With coal No. II (Germania) a marked change takes place by treating with oxygen at 135°C. This change consists of an addition in weight and a considerable loss of carbon dioxide and water, and this, we think, proves our assertion. Of course it is not necessary in order to change to an inflammable coal that the above must take place throughout the entire coal. It is sufficient if it happens in certain localities or perhaps only at the surface of small coal particles. That the addition in weight which takes place in oxidation, caused by the taking up of oxygen, is not substantially less in the less inflammable coals, with the exception of the altogether uninflammable coal marked Nixon Navigation, rests clearly on similar reasons, (the same is found under Table 7), from the ultimate analysis of the oxidized coal showing the addition of oxygen and the loss of carbon and hydrogen. Altogether out of place in this respect is the uninflammable coal No. 1, Nixon Navigation, which oxidizes very slowly.

"The end product of the oxidation is clearly seen to be the humic acids, and from the humic number is found without possibility of contradiction how far the easily inflammable and oxidizable coals are above the others. Less easy to account for is the fluctuating value or amount of pyridin extract, especially when one sees the content of the original and oxidized coals; but one thing is certain, that in the majority of cases the extract grows with the degree of self-ignition and is increased by oxidation. The one exception is coal No. II, which is perhaps ascribable to imperfect methods.

"Our researches show that the organic parts of the coal play two different roles which have little to do with each other. That portion soluble in organic solvents seems of similar character and composition and perhaps of similar origin as the soluble portion of Braunkohle, for example, the so-called Montanwachs, only the coal extract contains more oxygen and is therefore probably of similar origin but changed by oxidation.

"That portion of the coal insoluble in organic solvents we look upon as the real coal substance probably formed from cellulose in the original wood; and it is that substance which on further oxidation yields the humic acids and which, although not altogether still in the main part, determines the self-ignition of the coal. It contains also the unsaturated compounds upon which the iodine addition rests, which in the iodine number express themselves quantitatively, and they run parallel with the capacity for oxidation; the remarkable fluctuation of the iodine number in the original and oxidized coals we leave for the present purposely untouched.

"But, since the iodine number is so easy to determine, one has in the main a practicable means next after the Maumene number for determining the degree of danger from fire of the coal."

Summarizing their work it is seen that spontaneous combustibility increases with the following:—

1. Moisture at 105°.
2. Brittleness.
3. Iodine number.

4. Maumene number.
5. Humus number.

Graefe[1] noted that naturally weathered coal contains more ash, is of a lower calorific value, and on distillation gives less tar but has a higher paraffin content than the fresh coal.

Erdmann and Stolzenberg[2] found the work of Graefe to be in accord with the assumption that it is the unsaturated bodies, viz., the humus, that undergo slow oxidation. That the humus is the unsaturated body is shown by the fact that it absorbs large amounts of bromine without the evolution of hydrobromic acid, and also that it has a vigorous reaction with ozone. The humus can be extracted from the coal with alkali and separates on acidifying. A current of oxygen containing 2 per cent of ozone passed over humus in a U-tube at the rate of 500 c. c. per minute causing combustion in 23 minutes. Briquet coals coarsely powdered and moistened took fire in about 70 minutes; while dry, the temperature did not rise over 48°C. These experiments lead the authors to the conclusion that the self-ignition of small coal is due to the action of ozone.

Dry pyrite showed no increase of temperature; moist, only a 12° rise. A mixture of humus and 10 per cent of powdered marcasite (crystalline pyrite) took longer to ignite than pure humus; consequently, pyrite is not the cause of spontaneous combustion in coals.

The self-ignition of coal is probably not determined by the ozone content of the air but rather by the production of ozone, which is found by the evaporation of moisture from the surface of the moist coal. In agreement with the above statement is the fact that fires in coal heaps occur more frequently on warm, sunny days after a rain where the surface evaporation is especially great. The ozone found under these conditions immediately begins to react with, and is absorbed by, the humus substances which break up by its action in the presence of water into carbon dioxide and saturated cleavage products such as humic acid. The heat produced by this reaction accumulates when sufficiently insulated, and the rising temperature also causes the more inactive atmospheric oxygen to react, so that under favorable conditions the temperature will rise to the ignition point.

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[1] Braunkohle, Vol. 6, 713.

[2] Braunkohle, Vol. 7, 69
Chemisches Centralblatt, Vol. 79, p. 456, Aug. 5, 1908.

The reaction of coals with ozone as first described is a measure of their tendency to spontaneous combustion.

Moist cellulose (filter paper) showed no rise in temperature in 2 per cent ozone, wheat bran rose only 4.5°, while cotton waste soaked in linseed oil ignited very quickly.

O. Boudouard[1], 1909, in his work on the oxidation of coals and the products resulting therefrom found that in contact with the air at 100°C. coal readily undergoes oxidation; the increase in weight, through absorption of oxygen, in some cases being as high as 10 per cent. After oxidation in this way, coal is found to contain humic acid and to have lost its power of coking. The author then extracted the humic acid by means of potassium hydroxide solution from seven varieties of coal, both before and after artificial oxidation. The results of the fourteen analyses show that the chemical constituents of the humic substances thus obtained correspond with one or more of the following formulas:—

1. $C_{18} H_{14} O_6$ (Bertholet and Andre)
2. $C_{18} H_{18} O_9$ (Malaguti)
3. $C_{18} H_{14} O_{11}$
4. $C_{18} H_{14} O_{11}$

and that the effect of oxidizing the coal is to diminish the carbon and increase the hydrogen and oxygen content of the humic substance yielded by the coal. Concentrated nitric acid causes more complete oxidation and increases the yield of humic acid.

In an attempt to account for the coking power of coal, several samples were submitted to the effect of various organic solvents. Beyond the extraction of a small amount of resinous matter, these solvents had little if any effect. Concentrated hydrochloric, sulphuric and nitric acids, also 25 per cent potassium hydroxide solution, and finally Schweitzer's reagent, were tried. Concentrated hydrochloric acid had no effect, concentrated sulphuric and nitric acids destroyed the coking power, the 25 per cent potassium hydroxide solution and Schweitzer's reagent reduced the coking power considerably. The successive action of the potassium hydroxide solution, hydrochloric acid and Schweitzer's reagent caused the total loss of coking power; the solubility of the cellulose-like substances in the Schweitzer's reagent is the explanation given for this result.

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[1] Bulletin de la Societe Chimique, Vol. 5, 365; 372; 377; 380.
Compte rend. 147, 986; 148, 284; 348.

The humic acids found in the oxidized non-coking coals are probably the carbohydrates of the original coal in a condensed and polymerised condition. (Note: The polyatomic alcohols, sugars, etc., furnish humic derivatives by condensation and dehydration under the influence of or in the presence of heat or alkalis and acids. These humic substances thus artificially prepared are found to be very similar in composition to those extracted from peats and lignites. These facts tend to substantiate Fremy's theory[1] of the formation of peats through the fermentation of vegetable matter and the subsequent formation of coal through the agencies of heat and pressure). The fact that anthracite has not the power to make coke is easily explained; this class of coals represents the furthest progress in the metamorphosis of the plant material which no longer contains cellulose. In fact the natural or oxidized anthracites are free from humic acid. Special attention must be given to the fact that even a minute amount of humic acid is sufficient instantly to cause the loss of coking power.

Dr. Haberman[2] found that coal stored for a long time became unfit for the manufacture of gas, and that the coals lost in gasifying and coking value and also in heating power. He claims that the spontaneous combustion of coal is due to the absorption of oxygen by the coal substance. He gives the result of a series of experiments on spontaneous ignition in which he used 200 kilograms and then heated these samples in a fire brick retort at 50°C. The coal was supplied with air at a temperature of 24°–26°C. and practically ignited in 36–39 hours. He found that coals that oxidized the most and gave the greatest rise in temperature absorbed the largest quantities of bromine.

Parr and Francis[3], working upon the modification of Illinois coals by a low temperature distillation, found that active oxidation was effected at an unexpectedly low temperature. They found that a considerable quantity of carbon dioxide was given off by the coal on distillation in an atmosphere of nitrogen and steam, and a much larger amount was given off when an atmosphere of oxygen was used. Under the latter condition an occasional rise of the temperature in the retort was noted, seemingly independent of the external source of heat. This fact led to a series of experiments wherein careful temperature observations were made and in which the outgoing gas could be tested for carbon dioxide. Using an atmosphere of pure oxygen, they found carbon dioxide evolved at about 120°C., the kind of coal seemingly being immaterial, for Illinois coal, Pittsburg gas coal, and anthracite were used. Ignition temperatures ranged from 160° to 300°C. Using air as an atmosphere, the initial appearance of carbon dioxide was about 135°, instead of 120° with pure oxygen. This result is what would be expected, for the dilution of oxygen in the air by nitrogen would retard or lessen the activity of oxygen. At 280° a rapid rise in the oxidation temperature took place, notwithstanding the cessation of the external heat. This fact was observed on a sample of Illinois bituminous powdered coal in an atmosphere of air. Seemingly, therefore, we have here an illustration of a type of combustion which, while still below the ignition point, is still self-supporting and would be continuous, depending upon the oxygen supply.

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[1] Comp. Rend. 88, p. 1048, (1879).

[2] Schillings' Jour. fur Gasbeleuchtung u. Wasserversorgung Vol. 49, p. 419.

[3] University of Illinois, Engineering Experiment Station, Bulletin 24. (1908)

White[1], in studying the oxygenation and weathering of coal, notes that, in general, the lower classes of coal take up oxygen on exposure to the air. This, together with some immediate loss of compressed volatile matter (cf. work of Parr and Barker) appears to mark the first phase of weathering. Later, and on prolonged exposure, there seems to be a considerable loss of carbon and hydrogen also, especially in the humic (ordinary) coals.

The weathering of the lower grades of coal, especially bituminous, lignites and peats, is marked by the accession of oxygen which is taken into combustion. This increase of the oxygen contents, which seems to indicate lack of equilibrium in the hydrocarbon compounds of the normal coal, readily permits a calorific deficiency which, on account of the high calorific value of oxygen, is often serious.

SUMMARY OF OPINIONS

Reviewing the literature given in the preceding chapter, it may be seen that opinions differ as to the real causes of spontaneous combustion. The leading factors may, however, be summed up as being the following:

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[1] U. S. Geol. Sur., Bulletin 382, "The Effect of Oxygen in Coal."

1. The kind of coal, in regard to its volatile matter.
2. The purity of the coal.
3. The presence of pyrite or other sulphur compounds.
4. The temperature of the coal.
5. The size of the coal.
6. The presence of occluded gases in the coal.
7. The presence of moisture.
8. The accessibility of oxygen.
9. Pressure on the coal.

1. *Kind of Coal.*—From the ignition temperatures given by Fayol, it may be seen that only those coals (such as lignites, bituminous and semi-bituminous) containing large amounts of volatile matter, are liable to ignite spontaneously, and that anthracite with its very low percentage of volatile matter is practically entirely excluded. The results of the work of O. Boudouard, on the coking power of coals, also substantiates this view, for in his work he found that those coals richest in volatile matter (carbohydrates, cellulose, etc.,) were most liable to spontaneous combustion.

2. *Purity of Coal.*—The work of our own government seems to indicate that coals of exceptional purity are more apt to heat up than coals containing large amounts of extraneous matter. This is probably due to the fact that very pure coals are able to condense and absorb the oxygen of the air much faster than other coals and so cause an increase in temperature, which finally results in the chemical combination of the oxygen and hydrogen occluded in the coal. This view is confirmed by the later work of Dennstedt and Bünz, who found that those coals causing spontaneous combustion or those coals which oxidized and increased in temperature most rapidly were remarkably free from mineral matter and pyrite.

3. *Presence of Pyrite.*—As to what part sulphur compounds, especially pyrite, play in the spontaneous ignition of coal, opinions differ greatly. Some believe pyrite to be the leading factor, while others believe it plays no part at all, or, if so, ascribe to it a position of minor importance and believe its action to be merely a subsidiary one. The oxidizing action of the air upon pyrites is, however, admitted, and the notion seems to be fairly general and

well established that pyritic oxidation tends to raise the temperature of the coal. On the other hand, it is seen from the work of Fayol, Dennstedt and Bünz, Threlfall and others that coals containing pyrite in a quantity too insignificant to be noticed are very apt to ignite spontaneously. The Newcastle coal of New South Wales is also a very good example of this class of coals.

Others, however, believe that the only influence of the pyrite is a mechanical one, in which the oxidation of the thin films of pyrite in the coal serves merely to break up the coal.

4. *Temperature of the Coal.*—Most of the authors agree that the temperature of the coal undoubtedly is one of the main factors in the whole subject of spontaneous combustion, for cases of spontaneous combustion have occurred time and again where probably they never would have occurred if there had not been an initial heating in some way or other. The New South Wales Commission thinks that the initial temperature of the coal at the time of storage or loading is one of the great factors in the subject of spontaneous combustion, the true danger of which has not heretofore been fully appreciated. Sources of heat seemingly insignificant are frequently the cause of bringing the temperature of the coal up to the danger point and so causing coals to ignite which, under carefully regulated conditions of storage, would not be at all dangerous. Numerous cases are on record where the cause of the spontaneous ignition of large coal stores and loads was finally traced back to initial heating from flues, steam pipes, or direct exposure to the sun. This increased temperature, whether coming from outside sources or from physical or chemical reactions within the coal, tends to accelerate the absorption of oxygen and thereby to raise the temperature of the coal. It also tends to drive out the inflammable gases occluded in the coal, and so greatly to accentuate the danger of spontaneous ignition.

5. *The Size of the Coal.*—That fine coal is a more active absorbent of oxygen and more liable to ignite spontaneously than large coal was shown as far back as 1868 by Richter. Practically all of the later experimenters in this field concede this to be true, for, having a greater surface, the fine particles can absorb much more oxygen than large lumps; and since this rapidity of absorption causes an increase in temperature, which in turn produces favorable conditions for further absorption and for chemical action between the oxygen of the air and the hydrogen of the coal,

the danger of spontaneous combustion is greatly increased.

Throughout the literature, warnings are found cautioning coal users and shippers against storing fine coal. Some have even advocated that only large lumps should be transported on shipboard and that these should be carefully packed by hand. The covering of coal piles with slack is to be avoided, also the coal should be handled as little as possible to avoid disintegration, for, in handling, the finer particles gradually sift down to the bottom of the pile where they accumulate and are a source of danger, inasmuch as at the center and bottom of the pile the most favorable conditions for spontaneous ignition exist. Here the coal is sufficiently insulated by the surrounding coal so as to retain all the heat that is generated. Air is accessible in sufficient amounts to cause oxidation, and still is not present in large enough amounts to conduct away the heat. The fact that friable coals are more prone to ignite spontaneously than coals not so friable, also seems to substantiate the above opinion. Dennstedt and Bünz in their work on this subject even went so far as to make a friability test on all the coals they worked with, for they conceded the danger arising from the fine coal with its great avidity for oxygen, and recommended that they considered safe to transport on board ship only those coals passing a certain standard in their friability test.

6. *Occluded Gases in the Coal.*—While it is now a well known fact that gases of an inflammable nature are occluded in coal, their relation to the spontaneous ignition of coal has not yet been clearly established. Whether the gases occluded in the coal are the real cause of spontaneous ignition is doubtful, but if the coal becomes heated up by oxidation or some other cause to a temperature high enough for the oxygen of the air to unite with these gases, then it is seen that the presence of these gases constitutes a source of danger, and then coals with large amounts of gases occluded in them would be more liable to ignite than coals containing smaller amounts of these gases.

7. *The Presence of Moisture.*—Opinions differ greatly as to what part moisture in the coal plays in the spontaneous combustion of the same. Some, as Doane, believe the moisture content of the air-dry coal to be a direct index of its power to ignite spontaneously. Evidence given to the New South Wales Commission and also the British Commission shows that coal piles are more

apt to take fire during warm weather following showers than at other times, although Fayol, as a result of experimental work, claims that the influence of the weather on coal heaps has not been sufficiently marked to be observable. Erdmann and Stolzenberg believe the spontaneous combustion of coal to be due to the formation of ozone by the action of the sun on warm, sunny days following a rain, when the surface evaporation is especially great. If this is true, moisture plays a more important part in the phenomena of spontaneous combustion than has heretofore been ascribed to it.

That the presence of moisture materially assists the pyritic oxidation is generally conceded, although whether it causes an increase in temperature or merely a disintegration of the coal due to the formation of ferrous sulphate is a matter of dispute. Others believe that the only part that moisture plays is a mechanical one, where alternate freezing and thawing break up the coal into smaller particles and so expose more surface to the oxygen of the air. Again, it is thought that aside from increasing the pyritic oxidation, moisture acts as a catalytic agent between the carbon and hydrogen or unsaturated bodies of the coal and the oxygen of the air. Perhaps, as Erdmann and Stolzenberg have suggested, this reaction may consist of the formation of ozone which is immediately absorbed by the coal. This idea of catalytic action on the part of the moisture is substantiated to some extent by the fact that some coals containing minimum amounts of pyrite are nevertheless very liable to spontaneous ignition; and coals of this class, viz., the Newcastle and Scotch coals, have been known to cause fires.

8. *The Accessibility of Oxygen.*—That the combination of oxygen with the constituents of the coal causes a rise in temperature seems to be firmly established. Which particular constituent is the cause of the rise in temperature has not, however, been shown with any great degree of certainty. The presence of humic acid in the oxidized coal leads one to believe that the oxygen combines with some of the unsaturated humus bodies, such as the polysaccharides. That this humus substance is an unsaturated body is shown by the fact that it absorbs large amounts of bromine without the evolution of hydrobromic acid. In fact, Fischer goes so far as to devise a practical test to determine the safety of a coal by means of this reaction with bromine.

The idea is also held that the oxygen of the air combines directly with the carbon and hydrogen of the coal and so causes an increase in temperature. If amorphous carbon (charcoal and lampblack) can be oxidized to carbon dioxide on exposure to the air by means of bacteria, as has been proved by Potter,[1] the oxidation of the carbon of the coal is very probable.

The presence of oxygen is therefore to be avoided and the old idea of thoroughly ventilating the coal piles by free access of air is gradually being dropped, and at the present, authorities deem it advisable to keep the coal away from the air as much as possible, either by submerging it under water or storing the coal in covered concrete bins. If ventilation is used to lower the temperature of the coal, it should be through pipes, so that the cooling air cannot come in contact with the coal at all.

9. *Pressure on the Coal.*—The belief that pressure on the coal is one of the leading factors in the spontaneous ignition of coal seems to be gaining ground, and because of this fact it is advocated that coal heaps should not be any higher than 15 to 20 ft. The experience of Mr. Bush in this respect (see page 69) is certainly very startling, and in a store of that size the question is very probably one of pressure rather than radiation, although, in smaller storage units, it would probably be hard to decide whether the cause of the spontaneous combustion was due to pressure or lack of proper insulation of the heat generated within the pile.

It will be highly suggestive to compare this summary of opinions with the summary at the close of the experimental part of this work. The evidence of the oxidation of the various coal substances is there enumerated, and is in close agreement with the various investigators cited above, but the conclusions as to the part played by each is different; namely, that the oxidation (a) of the unsaturated humus bodies; and (b) of pyrites are direct contributors to the heat conditions which set in motion the more advanced and vigorous phases of oxidation. The activity of these initial stages is there designated as directly dependent upon fineness of division, moisture and accession of heat from physical or external sources. With these propositions established, the real importance of these initial activities is at once apparent and the fundamental principles which must be observed in remedial processes are made evident.

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[1] Proc. Roy. Soc. London (B), Vol. 80, p. 196.

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